We are the American Society of Photogrammetry; we should broaden our horizons to accommodate the needs of the industry. I believe we can do it. I know that the Society, in its Annual Meetings, will encourage free discusion, and free thinking. As Chairman of the Publications Committee, I encourage you to send me your ideas, your suggestions, your thoughts for symposia. We will then do our best to broaden these horizons.

# PHOTOGRAMMETRY IN ASTRONOMY*

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WITH the development of new lenses and cameras for aerial photography, it is quite evident that scientific personnel who create our modern precision maps from photographs are finding themselves face to face at certain crossroads with astronomers who have been matching their wits with photographic problems in astrometry for more than three quarters of a century. Mapping from high altitudes brings into play long focus cameras, equipped with lenses of astronomical quality and guided during exposures to compensate for the motion of the planes in which the cameras are mounted. Photographs taken under such conditions present problems in measurement and reduction to true scale that are almost comparable with those of the most exacting positional astronomy.

Just one hundred years ago, in July, 1850, William Cranch Bond, the director of Harvard College Observatory, placed a daguerreotype plate at the focus of the 15 inch equatorial telescope and obtained a successful photographic image of the brightest star in the northern sky, Alpha Lyrae. The extremely low sensitivity of his plates and the unsteadiness of the driving clock for the telescope prevented him from obtaining photographs of any fainter stars. After seven years, the new collodion process plates had appeared and a new driving mechanism for the telescope had been obtained. With these two advantages, Professor Bond was able to photograph stars as faint as sixth magnitude.

These early photographs of stars were not very satisfactory because of the color curve of the lenses which had been ground and polished for visual work. In the region of the spectrum where the photographic plate was sensitive, the slope of the color curve of the lens was very steep, so that it was impossible to obtain sharp images.

L. M. Rutherford was the first to repeat Professor Bond's experiments in 1858 specifically for the purpose of measuring the relative positions of stars. He used a telescope of $14\frac{1}{4}$ inches in aperture and of 14 foot focal length, and obtained a photograph of Gamma Virginis which readily showed a separation of $3''$ on collodion plates. Even though he had no problem from city lights in New York City at that time, he could not get any impression of stars of the sixth magnitude. It was the same problem of working with a lens that had been ground for the visual region of the spectrum. In 1861 he substituted a 13 inch mirror of 8 foot focal length which he strapped to his equatorial. His experiment with a reflector failed because of the vibrations from the city and from the atmosphere which spoiled the surface of his mirror. It was then that he decided that he must build a photographic lens. This was the first large astronomical objective to be corrected for violet or photographic light, and while it

* Paper read at the Sixteenth Annual Meeting of the Society, Washington, D. C., January 12, 1950.

would be rather useless for good visual work, it gave excellent photographic images. The bright star, Castor, could be photographed in one second whereas a visual achromatic lens would not produce an impression of the same star within ten seconds. In astronomical work such a difference in the efficiency of a lens made all of the difference between success and failure. For the first time Professor Rutherford and Dr. Gould of Columbia University Observatory obtained sharp point images of the Pleiades which could be used as a test for the determination of star positions from a photographic plate. Micrometric measurements of this plate showed conclusively that there were no changes of importance in the relative positions of these stars on the photograph, and the positions determined by visual observations of nearly fifty stars. The year 1866 is memorable in the history of astronomy and photography for that one result. More tests of the method followed with a series of photographs of star clusters, all of which gave very encouraging results.

The method of measurement adopted by Gould and Rutherford consisted in deriving polar coordinates for the star images. The radial coordinate was taken as the distance of a star from an arbitrary central star in terms of the micrometer units, while the angular coordinate was the position angle with respect to the trail of the central star or the direction of right ascension.

These first attempts to show the value of photography for the accurate charting and mapping of stars did not meet with universal acclaim. Among many astronomers, especially in Europe, there was great suspicion that star images could keep their true relative positions on a photographic plate after it had been soaked and treated in a succession of chemical baths.

As everyone experienced with photographic processes knows, there is an enormous difference in the thickness of a photographic emulsion when it is moist and when it is dry. In the emulsions used today, the expansion during development, fixing and washing may amount to a few hundred times. It is evident therefore that a rather skeptical attitude among those who first experimented with stellar photography was justifiable. This skepticism was healthy and constructive. It aroused the interest of men like Jacoby and Turner who evolved very precise methods and formulae for reducing the measurements and correcting them for the astronomer's age old problem of atmospheric refraction. It also inspired repeated comparative tests between Gould's original plates and new observations with careful visual observations. The net result of these careful tests was the universal recognition at the close of the last century, of the superiority of the photographic plate over the old visual methods.

In the 1880's the Henry brothers at the Paris Observatory had been doing a considerable amount of work on the observation of minor planets. To do this work visually requires a remarkable knowledge of star fields so that the eye can recognize the image of the minor planet which is passing through the field. Photography was a valuable tool to these men who recognized the need of permanent records of star fields which could be studied over and over without the discomfort of sweeping over numerous star fields with a visual telescope and continually consulting star charts. These men designed a photographic telescope of 34 centimeter aperture and 343 centimeter focus which they mounted beside a visual telescope of 24 centimeter aperture and 360 centimeter focal length. With the optical axes of these two telescopes perfectly parallel, it was possible to guide the instrument very accurately during the exposure. This instrument enabled the Henry brothers to photograph stars down to the sixteenth magnitude. It also was the first telescope to find the faint nebulosity which envelopes three of the stars in the Pleiades. A conclusive proof of the superiority of astronomical photography was further demonstrated by this instrument. Prior to its use, the best available chart of the Pleiades showed 625 stars, all carefully plotted by Wolf from visual observations. The Henry brothers instrument had approximately the same aperture as Wolf's, but the photograph of the Pleiades showed 1,421 stars.

One of the difficulties in studying photographs of star fields is the frequent occurrence of false images due to dust particles or emulsion flaws. To eliminate these, the Henry brothers devised a method of multiple exposures on the same plate in which the telescope was shifted slightly between each exposure and the three images of every star appeared at the vertices of a tiny triangle. This procedure was adopted later by cooperative observers who undertook the monumental task of mapping the entire sky through the program known as the Carte du Ciel.

The Carte du Ciel was planned by a group of fifty-six astronomers at the International Congress on Astronomical Photography at Paris in 1887. More than fifteen observatories in both hemispheres agreed to collaborate on a photographic map of the entire sky which would be as complete as possible. Each photograph would measure 2° on a side and have a scale of 1 mm. to 1′. A reseau consisting of cross-lines 5 mm. apart would be photographed on each plate, to facilitate the identification of stars. Furthermore each plate would be measured for the coordinates of the stars, and magnitude scales would also be determined.

This program required each of the cooperating observatories to provide itself with a suitable astrographic camera which would be devoted entirely to this work. At the time, perhaps no one of the original planners had a suspicion of the amount of labor that would be entailed in the successful completion of the task. Astronomical photography was in its infancy at that time, and many of the problems of accuracy in measurement were unknown. It is sufficient proof of the size of the task to note here that the work is still unfinished at this date, when the astronomical world is practically ready for its repetition. It has consumed the greater part of the efforts at many observatories during all of that time.

The most recent effort at mapping the entire sky is now under way at Mt. Palomar. The fast 48 inch Schmidt telescope is being used for this program, and when completed in about four years, photographs of the entire northern hemisphere down to the 19th magnitude will be available. This project however is not as pretentious as the Carte du Ciel. It will not involve a very accurate measurement of the position of all of the stars on each plate with a micrometer measuring engine, and the publication of these positions in a catalogue. Indeed that would be almost beyond the working time of the astronomers of several generations. But it will provide astronomers with maps of unexplored star regions that can be studied more in detail after they have been found on these photographs.

Star mapping by photography is not primarily intended for purposes of identification. Extreme accuracy is not necessary for that. But the accurate positions measured on photographic plates, which have been taken at different times, are the only source that an astronomer has of apparent motions of the stars on the celestial sphere. When the interval between photographs of the same star field amounts to several years, small changes in relative position of stars known as the proper motions become measurable. And by comparing positions of stars on plates taken six months apart, the astronomer can measure the parallax angle subtended at the star by the radius of the earth's orbit which is his base line for trigonometric parallaxes, and ultimately the fundamental unit on which all of his dimensions of the universe are based. These parallax measurements involve angles as small as a few hundredths or even thousandths of a second of arc; a problem that becomes more amazing in its achievement, if we compare it to a successful measurement of the angle subtended by a penny on the top of the Washington Monument from a distance of about 200 miles. Before the adoption of photographic methods for the determination of trigonometric parallaxes, there were only about 130 such parallaxes available. By 1930 some 6,000 stars had been measured, and this was at least a good working sample for statistical studies in the space distribution of stars. The number has been increasing in much greater proportions in the last two decades.

Before we take up a few points about the difficulties and sources of error in astronomical mapping of stars let me emphasize one more point of advantage that has meant much to research in this field. I have indicated in the story of the Henry brothers how photography saved much time and labor in observing, just for the sake of identifying stars and small planets. By superimposing plates taken at different times small objects which move past a background of stars, but which look like stars when viewed through an eyepiece of a visual telescope, can be found very quickly. Even when this motion is rather small, perhaps only a few seconds of arc, this method of discovery by superposition can be found from photographic plates with very little effort. The two photographs of the same star field are placed side by side in a frame, under a microscope with two objectives. A shutter arrangement operates so that the same area on the two plates is viewed alternately in the eyepiece, and any star which shows no apparent motion between the interval of the two exposures will remain unchanged in its appearance as the shutter changes the view from one plate to the other. But if there is a slight motion in a star, its photographic image will appear to oscillate back and forth in the eyepiece. This instrument is known as the "blink" microscope, and by increasing the magnifying power, very slight motions can be detected. With its aid, an observer can find first the stars which show definite motion, and he can select these for more precise measurement under a micrometer microscope, without going to the trouble of measuring all of the stars on the two plates in order to discover which ones show appreciable motions. This advantage, of course, cannot be had with the old visual methods.

A further proof of time saving by photographic methods was demonstrated by Dr. Frank Schlesinger[1] at Yerkes Observatory in 1903. Professor Barnard, who later made some of the best astronomical photographs of this half century, was at that time engaged in measuring the relative positions of the stars in four globular clusters, with a filar micrometer eyepiece on the 40 inch refractor at Yerkes Observatory. With the long focal length of 62 feet, this telescope provides a scale large enough to reduce accidental errors of measurement to a minimum. Schlesinger proposed to Barnard that they make a test of the relative accuracy of the measurements made visually with the filar micrometer and those made from photographs under a micrometer microscope. Professor Barnard agreed to this. While he continued his careful measuring of the cluster stars, Schlesinger took some photographs of the same clusters and measured them with the micrometer microscope. No one expected the result, for Professor Barnard was a very careful and skillful observer with the filar micrometer. After all comparisons had been made, the probable errors for the measurements from the photographs were only one third as large as those obtained with the filar micrometer by Professor Barnard. But above all, the time required for the

[1] Monthly Notices, *Royal Astronomical Soc.*, 87, 506, 1927.

taking of the photographs and their measurement was only one tenth of the hours spent at the eyepiece of the large telescope.

An empirical psychologist will tell any scientific research worker that accidental errors in making estimates or measurements are reduced by a factor which is proportional to the comfort of the observer while he makes his observations. This statement is borne out by Dr. Schlesinger's own experience with visual observing at a telescope where the astronomer must operate the filar micrometer while viewing the stars from many different positions. When the telescope is pointed at the zenith, the observation must be made with the head tilted back in a very uncomfortable position. He must also work in all sorts of temperatures. In the winter, he must bundle up in heavy clothes to keep warm while making his observations, which again adds to the discomfort and difficulties of operating a filar micrometer. We are told, however, that the discomfort from cold and heavy clothing had no seasonal or perceptible effect on the consistency of the observations made by an experienced observer. But the discomforts slowed down the work, and increased the strain so that much less was accomplished. It takes years of practice with the filar micrometer eyepiece before an observer can reproduce his own measures consistently without a serious personal equation and large accidental errors. Some observers have never attained the art or skill necessary for good results.

On the other hand, the measurement of photographic plates is usually done in a room where the temperature is about the same at all times. The observer always keeps his head inclined over the eyepiece at about the same angle, so that conditions in general are as conducive to comfort as possible. In about two weeks of practice, the results from the photographic measurements become consistent, and they can be repeated at a later time without any notable changes from the first measures.

The visual observer who is engaged in accurate star mapping is at another disadvantage which is partially overcome by the photograph. The scintillation of stars which is caused by the air currents at different densities and temperatures, imposes a very complex set of oscillations on the image of a star. I have had the experience for a few years in Manila, of observing the transits of time stars with a moving wire micrometer. As the time star enters the field of the transit instrument, the moving wire is set on the star and it is driven by a mechanism which keeps it on the star's image. To make the complete observation, the astronomer simply concentrates all of his attention to controlling the speed of the moving wire so that it does not deviate from the star. All of the time stars which I observed were within a few degrees of the zenith, but on many nights even for stars directly overhead, the oscillations due to atmospheric conditions made the work of guiding the moving wire very difficult. At times, the image of a star seemed to lag behind for more than a second and then suddenly leap ahead, so that the wire followed it through the field in a succession of short jerks. Some of these atmospheric displacements last longer than a few seconds of time and they cause more serious errors. Dr. Schlesinger observed long period deviations which lasted for more than twenty seconds and amounted to as much as $0.5''$ to either side of a mean position. It is clear that visual observations which require the observer to set his micrometer on each individual star over a period of several minutes cannot achieve perfect accuracy under such conditions. The photograph records these oscillations simultaneously for all stars in the relatively small area covered by the field of the telescope.

This atmospheric effect brings us, however, to one of the problems that the astronomer has to contend with in the measurement of star positions on a photographic plate. The oscillations of the star images about a point on the photographic emulsion gives the resulting images a diameter and shape which is different from the normal spurious disc. While all of the star images in a field under observation may go through the same gyrations during an exposure, the resulting images will differ in quality because of their difference in magnitude. Bright stars will show the effects of the oscillations more than faint stars which do not remain long enough in many of the distorted positions to leave an impression on the photographic plate.

Professor Phillip Fox studied this problem while measuring parallaxes of stars on photographic plates at Dearborn Observatory. He found that a difference of one magnitude between the star whose parallax was being measured and the general background stars with which its position was being compared could yield an error of 0.03″. An error of this size is serious because it is systematic and can vitiate the parallax measurement, and it warns the observer who determines star positions photographically that two stars whose positions are to be compared should differ by no more than about a tenth of a magnitude.

That problem has been practically eliminated by use of a device which cuts down the light of only the brighter star while the fainter stars reach the photographic plate without any interference. This is done by placing a small disc with a sector cut out of it immediately in front of the plate and rotating it rapidly. The image of the brighter star will be made only from the small flashes of light which come through the open sector as the disc rotates. The amount of light which is cut off can be regulated by adjusting the size of the sector. The rotating sector was adopted as soon as the magnitude error had been recognized, and it has been used almost universally in parallax programs.

The telescopes which were built before the beginning of this century were primarily designed for visual work. The lens makers, who ground and polished many of the objectives which are now famous for the work that has been done with them, were artisans who worked by rule of thumb in putting the finishing touches to the large lenses; and these final corrections are the perfections which have made the names of Clarke, Brashear, Merz and others famous among astronomers. With the introduction of photography in astronomical work, many of the great visual refractors became useless, until the development of suitable photographic correcting lenses which could be placed in front of the visual objective or somewhere in the optical system. Unless the photographic corrector equalled the original lens in quality, the photographic results were unsatisfactory. In many instances also the development of yellow sensitive photographic plates and the Wratten minus-blue filters was the solution to the problem of obtaining successful astronomical photographs with the old visual refractors. This combination of photographic plate and filter permitted the use of the instrument in the color range for which the lens had been originally designed.

But even with a telescope that gives excellent photographic images of stars for position measurements, there is an instrumental problem which arises from the difference in the colors of stars and atmospheric dispersion.[2] The dispersive property of the atmosphere will tend to raise the position of a white star towards the zenith, as compared to red stars. This lifting effect depends furthermore on the relative brightness of the stars. Bright white stars are lifted more toward the zenith than faint white stars; and in visual telescopes, bright red stars are shifted away from the zenith more than faint red stars. The total shift is proportional to the tangent of the zenith distance at the time of observation and

[2] *Astronomical Journal,* 46, 85, 1937; 47, 86, 1938.

to the magnitude of the stars. The ultimate result of this source of error is a tendency to make the scale of the plate progressively larger for red stars than for white; and in the case of a series of position plates taken with a Ross type 5 inch lens of 35 inch focal length in Johannesburg, South Africa, the dispersion effect amounted to 0.23″ per 100 mm between the red M type and white A type stars. This is about one part in 43,000. Ultimately, the amount of this effect will depend upon the type of lens, the selective absorption of the optical system and the photographic plate and filter used. Dr. Schlesinger finds that in the case of the Ross type lens, the effect was due to the fact that the second Gaussian point of the lens was slightly dependent on the wave-length of the transmitted beam. The magnitude factor in this source of error is best controlled by the use of the rotating sector.

Finally, in the course of years of research and measurement, the errors due to shifts in the photographic emulsions have been analyzed and eliminated to a reasonable extent. These shifts are proportional to the area of the photographic plate over which measurements are made; and they are kept at a minimum by taking two or more exposures on the same plate and rotating it through 180° after each exposure. From a careful study of astronomical photographs, doubly exposed in that way, Dr. Gustave Land of Sproul Observatory[3] has found evidence that the emulsion shifts on glass plates are much greater than was originally estimated by Dr. Schlesinger in 1910. A maximum shift of 11 microns has been observed. No significant advantage could be found by drying the plates in an horizontal rather than a vertical position. The shift was reduced appreciably by soaking the plates in water before exposure, to relieve stresses in the emulsion, and then dehydrating them in alcohol, but the benefits of this process were offset by the loss of sensitivity. The error is kept negligibly small by keeping the configuration of comparison stars as small as possible, and averaging out the shift errors on the doubly exposed plates on which the images of two comparison stars would be 180° apart.

Other emulsion problems arise from attempting to measure star images which are very close together. This is the case in the photographic observation of double stars. We can name three causes[4] of the displacement of close star images on a photographic plate, two of which tend to draw the images together, and one which tends to increase the separation between them. First, there is the turbidity effect in the emulsion by which the star images spread during an exposure, and in the case of very close double stars the photographic images tend to overlap and coalesce. This is a growth from overexposure, and the light from both stars adds up in the overlapping portion of the images. The net result is a false estimate of the position of the true centers of the stars. Secondly, there is the gelatin or Ross effect which occurs between the time of developing and drying. An exposed region will dry faster than an unexposed region on a photographic plate. As the two star images dry more rapidly than the unexposed areas around them, they tend to draw themselves together. Lastly, there is the Kotinski effect which is due to the action of the developer. The developer is exhausted more readily between two close star images than at their outer edges. Hence the space between the star images will tend to be less dense and the effect will counteract in part the first of these three sources of error, the turbidity effect. It is not serious in normally exposed star images, but it is very evident in overexposed ones.

There is no need to add here that such precision cannot be attained with

[3] *Astronomical Journal*, 50, 51, 1942.

[4] *Mees-Theory of the Photographic Process*, 906, 1942.

photographic film. Despite the risk of breakage, and the difficulties of bending glass plates to match the curvature of focal planes in certain telescopes, the temperature coefficients and hydroscopic properties of a film base would add disadvantages that could not be outweighed. Presumably a suitable flexible base will soon be found that will replace glass, but until that time comes, I expect to find the terrestrial photogrammetrist meeting the astronomers at the crossroad where glass plates become a necessity as their own work approaches more and more to the precision requirements of astrometry. I hope that this rather brief review of our problems has helped to suggest some solutions to your own problems.

# SHORAN FOR THE PHOTOGRAMMETRIST*

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## INTRODUCTION

THE most direct application of Shoran to the compilation of photogrammetric maps is its use in controlling aerial photography. The technique employed is somewhat analogous to the well-known transit intersection method except that a distance-measuring, rather than an angle-measuring, instrument is used. Positions are established by electronically measuring the distance from a photographic aircraft to each of two ground stations at the instant of exposure of the aerial camera (see Figure 1).

These "airline" distances must first be reduced to their corresponding ground lengths before the triangle can be solved to obtain horizontal position of the airplane. It is necessary, of course, to know the distance of the "base line" between the ground stations. Normally, this is accomplished by selecting ground sites near existing triangulation stations and making the necessary ties by a short transit and tape traverse.

It is this photogrammetric application of Shoran that has received attention at the Engineer Research and Development Laboratories under a project with which the writer has been connected. The general plan of research and over-all objectives of the investigation was supplied by the Chief of Engineers, and was designed to provide results that could be utilized in fulfilling requirements of the U. S. Army mapping plan.

The first and, in fact, the only test photography available to date, has been coverage that was flown in 1946 with Shoran equipment modified very little from the original bombing model. The accuracy attained on the tests was given in a paper presented by Mr. Lorenz at the 1946 Semi-annual Meeting of the Society in Dayton. To review these results briefly, it was found that the positions contained both a constant and a random error.

The constant error, which results in a shift of the finished map sheet with respect to the ground stations, was found to be less than 40 feet with careful calibration of the equipment. In addition, the individual positions were found to contain random errors of about $\pm 125$ feet or less on 90 per cent of the points. However, when multiplex methods were used to "average out" these individual

* This paper has been cleared for publication by both the Office, Chief of Engineers and the Department of Defense. It was read at the Sixteenth Annual Meeting of the Society, Washington, D. C., January 12, 1950.

NOTE: Comments on this paper are invited. To ensure consideration for publication in the September issue, receipt before July 15 is necessary.