THE BALLISTIC CAMERA AND ITS APPLICATION TO RANGE BOMBING

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IN ORDER to compute bombing tables for use by Army Air Corps bombardiers, it is first necessary by means of "range bombing," to determine experimentally under known atmospheric conditions the horizontal distance or "range" a given type bomb will carry when released from various altitudes and at various speeds. Prior to World War II the aircraft used for range bombing seldom flew higher than 25,000 feet or faster than 175 mi./hr. true air speed, and the ground tracking instrumentation for measuring the position and velocity of the aircraft at the instant of bomb release was inadequate for higher altitudes and greater air speeds. In December 1941 the Ballistic Research Laboratory of Aberdeen Proving Ground, Maryland, was charged with the responsibility of developing instrumentation capable of tracking range bombing aircraft flying at any elevation and air speed conceivably attainable by any type of aircraft which might be constructed during the course of the war. To fulfil this responsibility the Ballistic Research Laboratory availed itself of the services of astronomers and of the techniques of photographic astrometry.

During the past half century astronomers have photographed the entire heavens by means of long focal-length cameras attached to equatorial mounts, have painstakingly measured the rectangular coordinates of the hundreds of faint star images to be found on each photographic plate, and have filed the measurements away in the form of "Astrographic Catalogs" and charts, for future reference. Many of the brighter stars whose photographic images appear on the plates along with the host of fainter star images, have had their spherical coordinates in right ascension and declination determined to the fraction of a second of arc by other astronomers employing meridian circles. By reference to the meridian circle positions, the positions of all the fainter stars may when needed be found with a comparable accuracy, by means of the techniques of photographic astrometry. It was only natural, therefore, that astronomers called in for advice by the "BRL," would envision an airplane carrying a light, like a star, to be photographed from the ground at regular intervals by means of astrometric type cameras, with whose inherent accuracy they were well acquainted. The light would need to be of sufficient brightness to be photographed in the daytime, however, as range bombing at night is impracticable. At all events the astronomers had confidence that astrometric methods could be successfully applied to the problem of range bombing.

The problem at hand was solved for war time operation by installing an "Edgerton" type stroboscopic lamp within the under side of an airplane, aimed downward to emit a bright flash of light every second, and by photographing these periodic flashes during daylight range bombing operations from two widely separated ground stations by means of two so-called "ballistic cameras" conceived and developed for this work. The two ballistic cameras are equipped with Goerz Dagor F/6.8 lenses of 12-inch focal length, and are aimed vertically. They employ 8×10 inch glass photographic plates, on which the course of the airplane as observed from each station is recorded as a series of small black dots, the photographic images of the flashing light. From accurate measurement of the two photographic negatives, and by means of subsequent computations, the position of the airplane (strictly, the position of the flashing light) is determinable at seconds intervals with a high degree of precision and accuracy, in terms of rectangular coordinates. The velocity components of the airplane at any instant are then available by simple differencing. The object of the experimentation is to determine the space position and the velocity components at the instant of bomb release. Since the bomb release will not likely occur simultaneously with any one flash point, both the instants of flash and the instant of bomb release are recorded upon a high speed string galvanometer recording oscillograph, or "chronograph," as it is called for short, by means of frequency modulated radio signals. The chronographic record is correlated with the series of images on the ballistic camera plates by omitting flashes for two seconds, along with the corresponding flashing light "pips" on the chronographic tape. Thus, the chronographic record permits interpolation to determine the position and velocity components of the airplane at the instant of actual bomb release. The locations of the ballistic cameras are tied in with the target area by accurate survey, so that the bomb impact position is readily measureable in the same system of coordinates. In addition a pattern of eight geophones blanketing the target area and recording on additional channels of the chronograph, permits accurate determination of the time of flight of the bomb. (In range bombing the bombs are dropped inert loaded so that the use of geophones within the target area is practicable.) The equipment described was set up in the Mojave desert in 1944, and over 2,500 bombs were dropped during the ensuing two years, thus greatly facilitating the production of bombing tables during this critical period of the war. The ballistic camera instrumentation will yield the position of an airplane flying at 7 miles elevation with a probable error of $\pm$ 1.7 feet in the horizontal coordinates and ± 10 feet in elevation. The corresponding velocity components are determined from smoothed curves covering the 10 seconds interval just prior to release with probable errors of $\pm$ 0.15 ft./sec. in the horizontal and ± 0.5 ft./sec. in the vertical components.

From the photogrammetric point of view the operation and the mathematical theory of the ballistic cameras are of the greater interest. The operating principle of the cameras can be understood by examination of Figure 1, which is a photograph of "Station A" ballistic camera with rotating shutter and sky screen assembly. The ballistic camera lens objectives in their cell assemblies are attached to the respective cameras by means of fixed focus adapters constructed subsequent to focal tests. Rigidly attached within each camera are two fiducial mark optical systems, each of which images a pattern of five illuminated pin holes upon the photographic plate. After exposure and development these image patterns accurately define the position of each photographic plate relative to the camera, according to the relationship existing at the time of exposure. Actually, only the central image of each pattern is used, the pattern as a whole being for identification purposes. Level adjustments are provided, to permit rendering the camera vertical, or near vertical. Also, level rests are provided in two coordinates to permit precision level measurements of the inclination of the camera as defined by the plane of the photographic plate. A 12-power fixed focus telescope rigidly attached to the side of each camera, together with an azimuthal adjustment device for rotating the entire camera assembly, permits the camera azimuthal orientation to be held constant within $\pm 0.25'$ (minute of arc). The stability with which the adjustments are maintained, plus the accuracy attained in measuring the existing residual inclination of the camera, are important among the factors which have led to the attainment of high accuracy in the space coordinates of the flash points. The period of extended exposure to the series of Edgerton light flashes is controlled by means of external solenoid

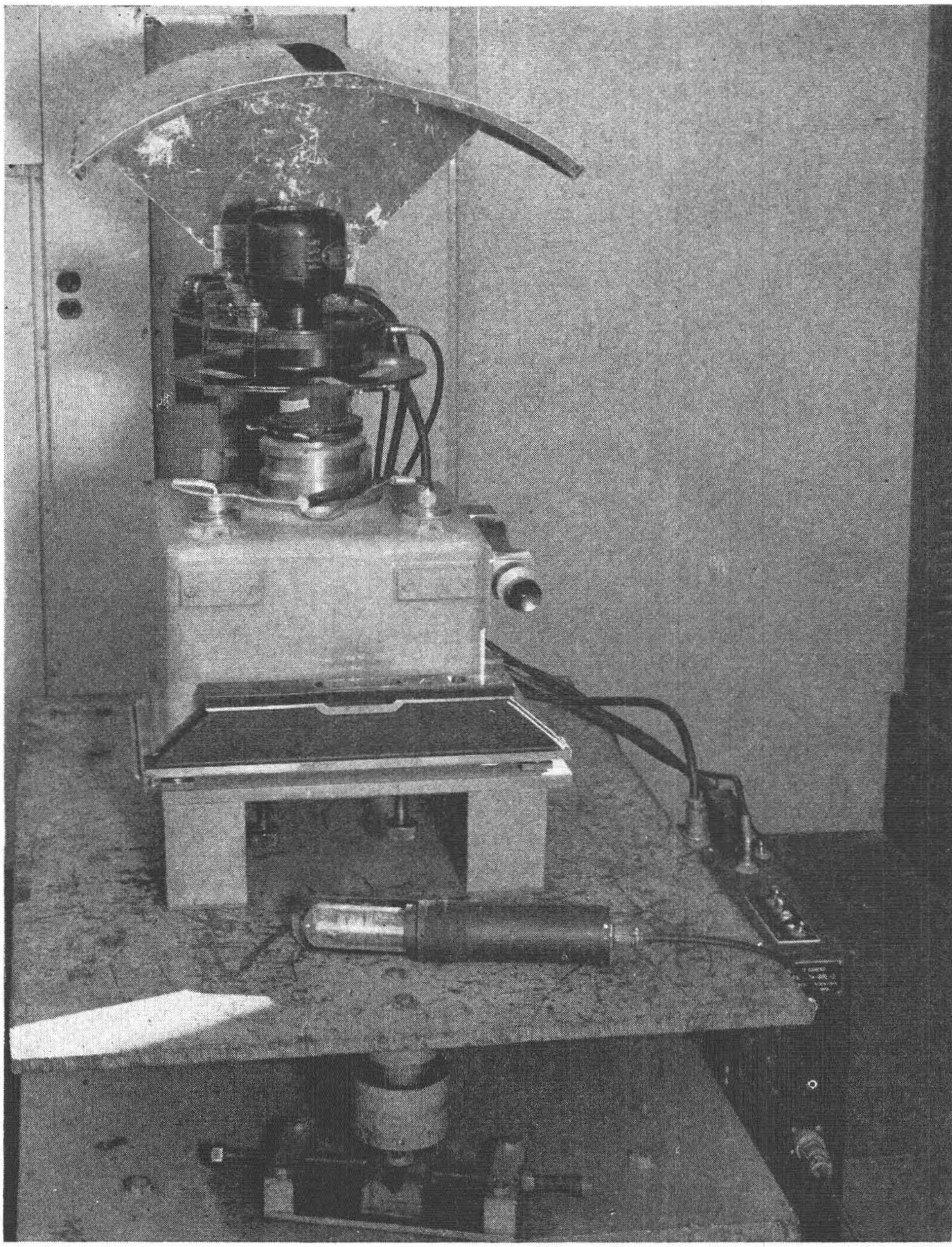

FIG. 1. Ballistic Camera.

operated shutters, which render the ballistic camera lens systems "open," or "shut." In this way both cameras are opened simultaneously to begin the period of tracking, and no dependence is made of the Batax shutter with which the Goerz lenses are provided, except for the use of the iris diaphragm. Experience indicated that the Eastman 103-G spectroscopic plate, with medium yellow color filter is an advantageous combination for daylight photography of the flashing light. The rotating shutter assembly, visible in Figure 1, consists of two 9-inch discs driven by a 110 volt synchronous motor, the lower disc rotating thirty times per second, and the upper disc once per second. Each disc contains a hole of 1-inch diameter near its periphery, the two holes coming into conjunction over the lens once each second. As the two holes come into conjunction, the lens (set at F/32) is effectively opened for about 1/1,000 second, during which interval the Edgerton light on the plane is caused to flash, its light entering the camera and producing an image on the photographic plate. Because of the extremely short duration of the exposures, and by further reduction of sky illumination by means of the "sky screen," an airplane can be photographed over the entire field of view of the camera, with an occasion as many as ninety or one hundred exposures on a single plate. The Edgerton light on the plane is triggered by means of a frequency modulated radio signal emanating from a transmitter at ballistic camera Station A. The signal which trips the flashing light is activated photoelectrically by a narrow beam of light which gains passage through the discs of the rotating shutters once each second, when two slots in the respective discs coincide for a brief period in the line of the rays. The two slots are so cut in the discs that the photoelectric action occurs at the same time the two peripheral holes which produce the photographic exposure come into conjunction over the camera A lens objective. Thus the exposures at camera A are automatically in near synchronization with the flashes from the Edgerton light on the plane. The rotating shutters over the ballistic camera at "Station B" are run at the same speed as those at camera A. The same speed is maintained by running a direct line to Station B from the low voltage frequency standard at Station A, this initially weak current then being amplified electronically (as at Station A) to 110 volts by means of power from a portable generator. At the same time, a special receiver at each station picks up the flashing light radio signal being transmitted from Station A, to operate a small Edgerton hand lamp. By means of the stroboscopic view of the discs provided by the hand lamp, and by means for adjusting the rotating discs, the camera operators can obtain accurate synchronization of their rotating disc shutters with the flashing light on the airplane. The sky screen, visible in Figure 1, is essentially a dark screen carried some 12 inches above the lens, and which obscures all direct sky illumination except that entering through a narrow slot approximately an inch in width. As the airplane advances down the course, the sky screen is rotated at such a rate as to keep the plane within the slot, as "seen" from the lens. The rays from the flashing light are thus never lost, whereas, upon the occasion of each exposure, only a small strip of the photographic plate is exposed to sky illumination. By employing the sky screen the lens aperture may be made larger than would otherwise be possible, thus increasing the light gathering power with respect to the rays from the flashing light. As stated before, with the aid of the sky screen a plane at 7 miles elevation may be tracked for 80 or 90 seconds, or until it is out of the field of view. Without the screen, not only would a smaller aperture have to be used, but the number of allowable exposures would be considerably smaller. The tracking of the plane by the sky screen is accomplished by means of a parallel motion elbow-type tracking telescope mounted outside the trailer (not visible in Figure 1).

The end products of the ballistic camera measurements are the so-called "standard coordinates," ξ and η, of the flash points, by means of which the rectangular space coordinates of the flash points may subsequently be computed. The significance of the standard coordinates ξ_1, η_1, as measured by ballistic camera A, and of ξ_2, η_2, as measured by ballistic camera B, are illustrated by the example of Figure 2. Of the three mutually perpendicular reference axes which radiate from the lens of camera B, one is vertical, and a second lies in the same azimuthal plane as the base line. A similar and parallel set of axes is established with origin at the lens of camera A. Thus in the illustrative example of Figure 2 the h' axis through A does not coincide with the plumb line at A, but instead parallels the h axis of camera B. Considering the standard coordinates ξ_1, η_1, and ξ_2, η_2, as tangents of the angles indicated in Figure 2, it is easily verified that the

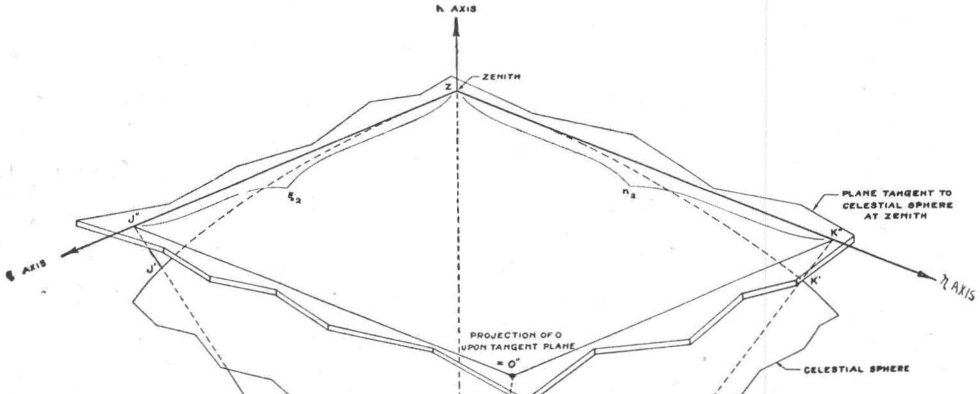

FIG. 2. Space Coordinates of Object Point O, as Determined from Ballistic Camera Measurement.

space coordinates, b, a, h, of the flash point O are obtainable by solution of the equations,

$$
\begin{aligned}
a - D &= \xi_1(h - \Delta h) \\
a &= \xi_2 h \\
b &= \eta_1(h - \Delta h) = \eta_2 h
\end{aligned}
\tag{1}
$$

in which D is the length of the base line, and in which h is the separation of the horizontal plane through B and the paralleling plane through A. The standard coordinates, ξ and η, may also be envisioned as rectangular coordinates in a plane tangent to the celestial sphere at the point pierced by the h (or h') axis, as is fully illustrated by Figure 2 for the case of camera B, the unit of length being the radius of the celestial sphere. As a further consideration, it is possible to imagine the ξ and η axes which are pictured on the plane tangent to the celestial sphere as optically imaged upon the photographic plate (which parallels the tangent plane). Thus, rectangular axes of standard coordinates are present on each plate (in theory, though invisible), to which the photographic image of any object point such as O may be referred. If the coordinates of the image of O could be directly measured in millimeters relative to the hypothetical ξ and η axes as "imaged" on the plate, and then divided by the focal length of the camera objective in units of millimeters, the quotients obtained would be the desired values of ξ and η, neglecting for the moment such refinements as allowance for optical distortion and atmospheric refraction. Practically an optical image of the axes of standard coordinates does not appear on the photographic plate in substance, and it is therefore impossible to measure the standard coordinates of O directly. To obtain the standard coordinates of O it is necessary to establish a mathematical relationship between the coordinates of O that are actually measurable on the plate, and the system of standard coordinates whose axes are invisible on the photographic plate.

The coordinates actually measurable are the comparator coordinates, assumed rectangular for the moment, and the desired relationship is obtained through the study of star trail calibration photographs which are taken at night. If the camera lens is left open for a precisely timed interval of one minute, at night, numerous star trails will be recorded upon the plate, each of whose standard coordinates can be computed with high accuracy on the basis of the individual star's apparent right ascension and declination, combined with the terrestrial latitude of the camera station and the sidereal time of the mid-exposure. There is thus established by computation the standard coordinates of each of a selected group of stars whose trailed images appear on the photographic plate. The desired relationship between the standard coordinates as computed for each star and the comparator coordinates x, y, is

$$\xi = \frac{x}{f}\cos\theta + \frac{y}{f}\sin\theta + \frac{n}{f} \tag{2}$$

$$\eta = -\frac{x}{f}\sin\theta + \frac{y}{f}\cos\theta + \frac{r}{f}, \tag{3}$$

based on the formulas of analytical geometry relating two systems of rectangular coordinates whose points of origin do not necessarily coincide and whose axes are inclined to each other by the angle θ. The measured coordinates x, y, and the unknown constants of translation, n and r, all of which are in units of millimeters, are reduced to units of standard coordinates through division by f, the focal length of the camera in units of millimeters.

At this point it is desirable to explain certain features concerning the measurement of the photographic plates. The measurements are made with the aid of a precision one-screw comparator specially constructed for the ballistic camera work by D. W. Mann Precision Instruments. Previous to the start of actual measurements the stage of the comparator may be disconnected from the driving nut, and may be moved freely back and forth in a motion parallel with the principal guiding way. Thus prior to the "x" measurements, it is easy to align any plate in the machine so that the direction defined by the two artificial fiducial marks (previously described) is parallel with the principal guiding way. The same technique is employed in the "y" measurements where the line joining the fiducial marks is rendered parallel with the secondary guiding way. By means of this technique the orientation angle θ of equations (2) and (3) may be held constant for the various plates taken with a given camera. The focal length f of the given camera may also be assumed to remain constant. It is therefore feasible to rewrite equations (2) and (3) as

$$\xi = Lx + My + N \tag{4}$$

$$\eta = -Mx + Ly + R, \tag{5}$$

where the substitutions made are obvious. The quantities L, M, N, and R are termed "plate constants." Assuming θ and f to remain constant, the plate constants L and M, once determined from a star trail photograph, will serve for the reduction of subsequent range bombing plates. Although the star trail plate will also yield values for the constants of translation, N and R, these values will apply to the star trail plate only. It is impracticable to attempt to obtain the same constants of translation with each insertion of a plate in the comparator, and these must be separately determined for each plate to be measured. As to the solution for the plate constants L and M, based on a star trail photograph, and also as to the solution for N and R as applicable to that particular plate, suppose that a group of twelve (the number customarily employed) star trails has been decided upon, the individual trails being well distributed over the plate. Suppose further, that ξ and η have been computed for each star and that the corresponding comparator coordinates, x, y, have been measured. Equations (4) and (5) may then be formulated for the case of each star, and the entire assemblage solved for L, M, N and R, either by least squares or by the simpler process of algebraic elimination. After the plate constants are at hand, the standard coordinates of each fiducial mark on the star trail plate may be computed by means of (4) and (5), based on the measured x, y, of each fiducial mark.

The standard coordinates of the fiducial marks are of importance in the reduction of the daytime range bombing plates. Since the fiducial marks are produced by optical projectors fixed within the camera, and since the camera orientation is held constant, or nearly so—deviations being allowed for, the standard coordinates of the fiducial marks may (for illustrative purposes and for the time being) be assumed to remain constant for range bombing plates subsequent to the star trail calibration. Based on this assumption it is apparent that the constants of translation N and R applicable to any given range bombing plate, may be found by means of equations (4) and (5), inserting therein the known values of the standard coordinates of the fiducial marks, the measured comparator coordinates x, y, and the values of L and M as found from the star trail calibration photographs.

The process of calibration as described above must of course be carried out separately for each of the ballistic cameras.

For simplicity of explanation the foregoing general description of the ballistic camera methods has ignored a number of refinements in theory, the application of which is important in attaining the highest possible accuracy, and in addition has assumed the cameras to be in perfect orientation relative to a set of axes chosen as especially suitable for illustrative purposes. In actual operations it is impractical to attempt to achieve perfect leveling of camera B and to adjust the axis of camera A to exact parallelism with the axis of camera B. In order to establish a workable field technique, it was therefore decided to level each camera only to the extent needed to permit direct and reverse level readings to be taken in the two horizontal coordinate directions at each camera station. The inclination of the plane of the photographic plate is thereby measured to a few seconds of arc, thus determining the corresponding perpendicular space direction of the "instrumental axis," the latter being defined as the perpendicular dropped from the second nodal point of the lens system upon the plane of the photographic plate. For a given plate of a bombing run, and in accordance with the leveling technique established, the standard coordinates of the flash points as directly evaluated by means of equations (4) and (5) would refer to the direction of the instrumental axis as polar reference axis. In the ballistic camera work such coordinates, compensated for the effect of optical distortion, have been termed "instrumental" standard coordinates, and are denoted ξ^* and η^*. The instrumental standard coordinates ξ^* and η^* of a space point having been evaluated, and the direction of the instrumental axis being known from the level readings, the standard coordinates referred to the desired zenithal direction may be obtained by application of so-called "tilt corrections" in the two horizontal coordinate directions. The values of the tilt corrections are given by the equations

$$\Delta\xi = -\lambda - (\xi^2\lambda + \xi\eta\mu), \tag{6}$$

$$\Delta\eta = -\mu - (\eta^2\mu + \eta\xi\lambda), \tag{7}$$

where λ and μ (in units of radians) represent the amount of the $+\xi$ and $+\eta$ components of the inclination of the instrumental axis to the desired zenithal direction. Obviously the instrumental standard coordinates from camera A and camera B may as easily be referred to *any* zenithal direction as to the zenithal direction at *B*. In practice the zenithal direction chosen is that at the point of bomb release, for the reason that the resulting bomb release data are then directly applicable to trajectory computations. Since in ballistic camera work the magnitude of λ and μ will not exceed 2 minutes of arc (0.000010 radians) and the value of ξ and η will not exceed 0.3 at most, the higher order terms within the curved brackets of equations (6) and (7) may be dropped as not seriously affecting the sixth decimal place of the computations. Practically, therefore, the corrections for tilt are constant over the plate for the case of the ballistic cameras, and may be applied as single increments added to the constants of translation, N and R.

Obviously the leveling technique described and the equations of tilt are applicable to the case of the star trail calibration photographs as well as to the photographs taken during range bombing. It is thus unnecessary to level the cameras perfectly before taking star trail calibration photographs.

The complete equations for determining the standard coordinates needed for the computation of the space coordinates of a flash point are

$$\xi = Lx + My + N + \Delta\xi^* + [d\xi + \delta\xi + \delta'\xi] \tag{8}$$

$$\eta = -Mx + Ly + R + \Delta\eta^* + \left[\pm\frac{\sin\epsilon}{f}y + d\eta + \delta\eta + \delta'\eta\right]. \tag{9}$$

As may be readily understood, the expressions, $Lx+My+N$, and $-Mx+Ly+R$, give approximate values for the instrumental standard coordinates $\xi^*$and η^*. The quantities $\Delta\xi^*$ and $\Delta\eta^*$ are the tilt increments, the application of which reduce ξ^* and η^* to the desired zenithal reference axes. The terms within the squared brackets denote various minor corrections representing refinements in theory to allow for all known factors appreciably affecting the accuracy of the final space coordinates. It is of interest that each of the quantities within the squared brackets may be tabulated against ξ and η as arguments. By reason of this circumstance it was possible to compile a table giving at a glance the numerical values of each of the squared brackets as a function of ξ and η. In practical computation the sum of the first four terms in the equations for ξ and η are first found, to serve as arguments for entering the table listing values for the squared brackets. The tabular values for the squared brackets are then applied to yield the final values of ξ and η.

It will be of interest to describe briefly the nature of the corrections represented by terms within the squared brackets of equations (8) and (9). The principal and secondary guiding ways of the Mann comparator are not exactly perpendicular by the amount of the small angle ϵ ($\epsilon = 31''$ in the case of the Mann comparator employed in this work). For this reason a correction, $\pm$ ($\sin \epsilon / f \cdot y$) must be applied to each comparator "y" coordinate to reduce to rectangular coordinates. The "+" sign applies to the case of camera B and the "−" sign to camera A. As can be readily appreciated the application of this correction causes no extra inconvenience in practice. It was for this reason that a closer approximation to exact perpendicularity was not specified in the contract for the Mann comparator.

The expressions $d\xi$ and $d\eta$ represent allowances for the ξ and η components of terrestrial atmospheric refraction evaluated in terms of standard coordinates. The expressions $\delta\xi$ and $\delta\eta$ represent compensatory corrections for the ξ and η components of the optical distortion of the Goerz Dagor lens system, as derived from analysis of star trail photographs taken with the lens at full aperture.

The expressions $\delta'\xi$ and $\delta'\eta$ are corrections which allow for a change in the optical distortion of the Goerz Dagor lens when the latter is stopped to F/32, the aperture used in the daylight range bombing photography. The necessity for this correction was revealed by analysis of experimental pairs of stellar exposures taken with a ballistic camera attached to the upper end of the 60-inch reflecting telescope of the Mount Wilson Observatory. By utilizing the driving mechanism of the 60-inch reflector, two time exposures of a star field could be impressed on a single ballistic camera photographic plate (shifting slightly between exposures), one of the exposures being made with the Dagor lens fully open (F/6.8) and the other with lens stopped to F/32, the aperture employed in the daylight range bombing photography of the flashing light. The duration of the exposures was adjusted to give the same limiting stellar magnitude with lens open and with lens stopped to F/32. From analysis of differential measurements between the various pairs of star images, the "F/6.8" and the "F/32" images, the variation of distortion with aperture was revealed as a function of axial distance. No change was found at 20° from the axis, but at 10° the F/32 images were systematically displaced away from the axis by 25 microns as a result of stopping down the lens. A parabolic relationship was adopted to represent this effect over the plate. Analysis of similar exposures taken with a yellow color filter before the lens disclosed the same effect, indicating that the effect was independent of color and was a function of diaphragm aperture only. As a by-product it was discovered that the "focal length" of the camera—defined in this case as the perpendicular distance from the second nodal point to the plane of the photographic emulsion—is greater by 0.075 mm. for yellow light than for blue. Since the blue light is predominately effective in the star trail calibration photographs, and since the daytime photography is performed using a yellow filter, consideration indicates that the scale of the ballistic camera plates as derived from the star trail plates should be decreased for reduction of the bombing plates. In other words, the value of f in equations (2) and (3) should be larger for the daylight plates taken with the yellow filter. This adjustment is regularly accomplished by multiplying the plate constants L_s and M_s as directly determined from star trail plates, by the factor 0.99975, to obtain the plate constants L and M of equations (8) and (9) for use in the reduction of the daylight range bombing plates.

The plate constants L_s and M_s are directly obtained from star trail photographs by means of the equations,

$$\xi_d^* = L_s x + M_s y + N_s \tag{10}$$

$$\eta_d^* = - M_s x + L_s y + R_s \pm \frac{\sin \epsilon}{f} y, \tag{11}$$

in which ξ_d^* and η_d^* represent the star's "distorted" instrumental standard coordinates, and in which the subscript "s" indicated that the plate constants are those directly obtained from the star trail photographs. In order to compute the distorted instrumental standard coordinates, ξ_d^* and η_d^*, of each star, preparatory to the solution of equations (10) and (11) for the plate constants L_s, M_s, N_s, and R_s, the standard coordinates of each star are first computed relative to the plane tangent to the celestial sphere at the zenith. During the course of this operation astronomical atmospheric refraction is applied to each star position. Proper tilt corrections are then applied to yield the corresponding standard coordinates in the plane tangent to the celestial sphere at the point pierced by the instrumental axis. Next, the distortion values $d\xi$ and $d\eta$ for full aperture are applied with proper algebraic sign to yield the star's distorted instrumental standard coordinates. The distorted instrumental standard coordinates define the physical position of the optical image of the star on the photographic plate, as affected by lens distortion, and relative to a point of origin taken where the instrumental axis pierces the photographic plate (frequently termed the "base" of the plate). The term, $\pm$ (sin $\epsilon/f)y$ has the same significance as in equations (8) and (9). For evaluation for use in equations (10) and (11) an approximate value of the focal length, f, is sufficient. After the plate constants L_s and M_s have been obtained by solution of (10) and (11), and after the instrumental standard coordinates of the fiducial marks have been computed by application of (10) and (11), all these values are multiplied by the factor 0.99975 to reduce to the scale of the daytime range bombing plates, as explained in the preceding paragraph.

A consideration not allowed for in equations (8) and (9), and which immediately comes to mind, is the possible effect of temperature on the plate constants. Will the plate constants as determined from star trail photographs, be directly applicable to photographs taken during the daytime when the temperature is higher by some 20° to 30° Fahrenheit? No allowance has been made for the effect of temperature variation because it has not been found possible to measure the magnitude of the effect with any degree of certainty. Both the camera box and the glass plate contract during the cooler evening temperature, and the resultant differential contraction, plus possible lens effects due to lower temperature, appears to affect the plate constants by amounts less than their probable errors. Plate constants from photographs taken on cold nights and on warm nights have not differed in a consistent enough manner to warrant a decision.

In conclusion it is of interest to relate that the two ballistic cameras under discussion were constructed by the Mount Wilson Observatory shop, except for the lens fittings, fiducial mark systems, and azimuthal sighting telescopes, which were constructed and installed by Aberdeen Proving Ground. Concurrently with the initial operations of 1944 in the Mojave Desert, the plate measuring and the computational work described was performed by a group of twelve Aberdeen Proving Ground personnel, a portion of these being military personnel, in office space kindly made available at Pasadena by the Director, Mount Wilson Observatory. During the 1945 program the measuring and computing was performed by a group of some twenty-five students of Occidental College, Los Angeles, who with their own supervisor worked under Army Ordnance contract, along with a nucleus group of six Aberdeen Proving Ground computers, four of the latter being military personnel.