PANEL
THE BALLISTIC CAMERA ACCURACY REVIEW PROJECT*

RCA SERVICE COMPANY PANEL DISCUSSION
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A. E. Glei	*Design and Operational Philosophy of Ballistic Camera Systems at the Atlantic Missile Range*
R. A. Gugel	*Calibration of Comparators for Ballistic Camera Data*
F. Collen	*Ballistic Camera Calibration by Stars*
R. A. Brown	*Ballistic Camera Stability at the Atlantic Missile Range*

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INTRODUCTION[1]

THE purpose of this panel is to present the results of a major effort at the Atlantic Missile Range to establish and to improve the geometrical quality of the Ballistic Camera System. The panel presentation covers each of the major areas of activity concerned with the determination and correction of errors of the AMR Ballistic Camera Systems required for calibration of new electronic tracking systems.

During past years, the Ballistic Camera System has been considered to be the accuracy standard at AMR with a prime mission of evaluation and calibration of other instrumentation systems, both optical and electronic. The state-of-the-art of electronic measuring has now reached the point where the geometrical quality required of the Ballistic Camera System necessitates a total residual standard error of 2 microns on the Ballistic Camera plate.

The technical elements of the Ballistic Camera System have been broken down into four major areas with each major area further subdivided into more detailed parts. Because of the complex inter-weaving of the technical elements and their dependence one upon the other, it has not been feasible to establish one or more elements as being the most critical area affecting system accuracy.

The Ballistic Camera Accuracy Review project is a two-phase operation: 1) the evaluation of the geometrical quality of the Ballistic Camera System as it is engineered at the present time; and 2) the calibration of this system so that increased geometrical quality may be obtained. In doing this, the entire BC System has been considered by its various components, such as:

a) The photogrammetric aspects, which include the theory and operation of the system for measuring.

b) The photometric aspects, which include the ability of the system to record and measure the light which passes through the optics and impinges onto the photo-receptive elements. The extension of photometrics concerns all aspects of: type of photographic environment; to the care, handling, processing, and storage of the emulsion and plate.

c) The optical aspects, which concern the actual glass which makes up the lens itself and tie in with the photometric characteristics.

d) The mechanical aspects, which concern the shutter, operation and vibration, and the camera mounting technique and stability.

e) The electronic aspects which concern

[1] This paper constitutes a condensation of the four papers presented on the panel.——*Editor.*

* Presented at the 29th Annual Meeting of the Society, The Shoreham Hotel, Washington, D. C., March 24–28, 1963.

TABLE 1

	Orientation			
	Focal Lengths			*Cumulative*
	115	*210*	*300*	
1959: s_0	3.5	3.7	4.3	3.8
s	—	—	—	0.9
1961: s_0	3.5	4.0	4.5	4.2
s	0.7	0.6	0.8	0.8

s_0 = standard error of unit weight.
s = standard deviation of data about the standard error of unit weight.
(All values are in microns.)

TABLE 2

Error budget for BC-300 Camera (from actual data)
Estimated: before BACAR

Orientation	s_0	s_0^2	s_0
Setting error	1.5μ	2.25	
Comparator error (STK1)	2.7	7.29	
Emulsion error	3.0	9.0	
Star catalogue error 0.7 sec	1.0	1.0	
Refraction error (stars) 0.2 sec	0.3	0.09	
		$[19.63]^{1/2}$ =	4.4μ 2″93

s = estimated standard deviation of standard error.
s_0 = standard error of unit weight.

the timing requirements of the system, the delays of the timing impulses in the communication system.

All of these——photogrammetric, photometric, optical, mechanical, and electronic——have been investigated from a calibration standpoint.

In order to establish the improvement, it was necessary to first evaluate the accuracy of the earlier Ballistic Camera data. Data were already on hand from 38 plates and 20 tests from the summer of 1959. In addition, data were accumulated from 103 plates and 36 tests from 1961. The measure of the accuracy of the systems can be obtained from analysis of the standard errors of unit weight from the orientations. These data are summarized in Table 1. Equivalent data are to be continuously accumulated on all future plates and tests.

The total errors computed from actual data were then subdivided into component errors as shown in Table 2.

The improvements brought about by Phase I of the BACAR work are expected to reduce the component errors as shown in Table 3. The data estimates are being validated by evaluation of actual data.

OPERATIONAL PROCEDURES

Astronomy is as old as man himself. Men have always been keenly interested in the heavenly bodies and have made many varied uses of the fact that the stars in the celestial sphere are basically fixed in relation to Earth. The ballistic camera operation employs this principle, using the stars as targets. By photographing a group of stars at a precise time, from a specific point on Earth, a so-called star calibration is made on the ballistic camera photographic plate.

The operation procedure for conducting star calibrations varies with the area of the celestial sphere being photographed, but in general is as follows. A few minutes prior to an event which is to be photographed, the camera is prepared for full operation. At the conclusion of this preparation the camera is not touched until the operation has been completed. A series of successive star exposures of 2, 1, ½, and ¼ seconds, separated by intervals of 30 seconds, are made. This produces, from each star in the field of view, four point images of varying length. The shutter is then closed and remains so, until it is time to record a series of missile-borne events along a given trajectory. The shutter is then opened (remote control) and data points are photographed as desired. After an elapsed time of from one to five minutes, the shutter

TABLE 3

Expected: after BACAR Phase I

Orientation	s	s_0^2	s_0
Setting error	1.5μ	2.25	
Comparator error (STK1)	1.0	1.0	
Emulsion error	1.0	1.0	
Star catalogue error 0.7 sec.	1.0	1.0	
Refraction error (stars) 0.2 sec.	0.3	0.09	
		$[5.34]^{1/2}$ =	2.3μ 1″54

is again closed, and within one minute the above calibration is repeated. The plate now consists of a series of missile-borne flashing—light images recorded against a background of hundreds of superb reference points provided by the star images.

As the precise time of each calibration exposure is recorded, the direction from the observing station to any recorded star can be accurately computed by means of standard astronomical formulas. From the plate measurements of at least three images of stars of known direction, it is possible to determine the precise orientation of the camera. In practice 20 to 30 stars are measured, and the orientation is computed from a least squares adjustment. Both the pre- and post-calibration stars are used in the reduction, and this makes possible detecting any significant change in orientation which may have occurred during the critical interval between calibrations.

Once the orientation of a camera has been computed, the directions from the camera to the recorded data points may be computed from the measured x and y plate coordinates of their images. The position of each missile point can then be determined by spatial triangulation of corresponding rays produced by three or more stations. Although two stations are sufficient for a triangulation with the system, three cameras are employed in a least squares triangulation. This not only leads to improved accuracy, but provides a very valuable check on the internal consistency of the system.

Two major problems encountered with the camera systems were: 1) the time accuracy of the shutter control signal system, and 2) the timing accuracy of the image source which is a strobe flash or a pyrotechnic flare in most applications.

In the shutter control system we were confronted with the problem of varying transmission time of signals to the widely scattered camera sites. From the BACAR efforts a system has been developed in which we use a Loran "C" receiver at each camera site to compute the precise delay times to each camera site.

The second problem, the actual flash time of the image source has also been solved. An improved ground photomultiplier system has been developed and one of the systems is used in each camera complex.

Comparator Calibration

A comparator may be described as a precision coordinate measuring instrument which has been manufactured and adjusted to meet a particular level of accuracy. If the instrument does not produce measurements of the desired accuracy, proper calibration procedures may be employed to improve the accuracy of the comparator coordinates. The limit which can be reached is determined by the setting precision obtained, the basic mechanical limits built into the instrument and the accuracy of the standards used for the calibrations.

Any comparator of the precision—leadscrew type is subject to several sources of systematic error. These are periodic leadscrew error, scale error, secular leadscrew error, weave and curvature of the ways, and nonperpendicularity of axes.

As part of the Ballistic Camera Accuracy Review Program, the comparators used for reading ballistic camera plates were to be calibrated to achieve a standard error of 1 micron. Time being a limiting factor, the methods selected were based on the availability of suitable calibrated standards. The standard available was a 240 mm. scale graduated at 1 mm. intervals and calibrated to an absolute standard error of 0.5 microns. This standard was used for the calibration of the leadscrew secular error and scale error. An uncalibrated scale 2 mm. long with graduation lines at 0.1 mm. intervals was used for the periodic leadscrew error calibration. The line width on these scales was approximately 10 microns. Plates were locally fabricated to provide 10-micron diameter reading points properly spaced for the calibration methods selected for calibrating the errors due to weave and curvature of the ways, and nonperpendicularity of axes.

The standard for the calibration of weave and curvature of the ways was obtained using a microndensitometer to project a reticle on a high resolution, ultra flat plate. A dot outlined by a crosshair pattern for easy identification provided the desired 10-micron images when the exposure was properly controlled. A line of 121 points spaced at 2 mm. intervals diagonally across the plate provided the desired 240 mm. span.

The standard for the calibration of nonperpendicularity of axes was obtained in the same manner as that described above except that a grid pattern was used instead of a line of points. A square grid pattern covering the entire plate at 20 mm. intervals provided a good selection of points to read for the calibration.

Lens Distortion

The primary purpose of the stellar camera lens distortion calibration is to obtain current and valid radial distortion coefficients for the metric cameras. The basic philosophy in lens distortion calibration is that in a true photogrammetric camera there exists a reasonable amount of radial distortion; but tangential distortion is considered to be negligible.

When the need for computing the lens distortion coefficients was first recognized, the time required to prepare an elaborate and sophisticated program was not available. The camera stellar orientation program was being used in the reduction and could be used to provide residual vectors uncorrected for radial distortion, but with all other biases or constant errors presumably removed. The means of meeting the calibration need was to prepare a computer program utilizing the orientation results to compute the distortion coefficients. In a short time these two programs were combined into one package which computed the orientation and distortion parameters simultaneously. In this earlier work, it was necessary to identify manually each star and to enter individually the proper catalogue information. A maximum of only 44 stars could be used as control points.

With the improved computer it was possible to store the Boss catalog on magnetic tape which could be conveniently available to the computer at all times. The first lens distortion programs on the new computer required that all stars be manually identified. However, the current program is so designed that all stars are automatically located and identified at the computer. It was also possible at this time to expand the adjustment from a 9-element solution (6 elements of orientation and 3 coefficients for radial distortion) to a 15-element solution. The 15 unknowns include: 6 orientation, 3 radial distortion, 3 refraction, and 3 tangential distortion parameters. The present program with storage for 400 control points is quite capable of solving for any or all of 17 elements. The two additional parameters are included to compute a point of symmetry.

The calibration exposures should be scheduled for a time during the night when one of the more dense star fields in the Milky Way is overhead. Even with a rich star field an insufficient number of stars occur for providing the desired redundancy if each star is used only once. For this reason multiple sets of exposures are used. The present computer program is designed to locate automatically the appropriate star in the catalog. This feature represents considerable saving in the time required to prepare the input for the computer.

Ballistic Camera Stability

Most of the vibrational disturbances of the Ballistic cameras were studied in the laboratory. Moving coil pickups with suitable amplifiers and pen chart recorders were used to measure the oscillations uncovered. Where a permanent shift of optical axis was to be studied, first surface mirrors were fastened to the parts of interest and their relative shifts were detected by means of autocollimators. It was necessary to mount all experimental gear on a heavy microflat bench to provide the stabilty necessary for measurements of this magnitude. After this portion of the work was completed, attention was turned to a field assessment of pedestal stability. In many cases a fabric shelter with zippered sides was set up over an exposed pier so that the latter could be exposed to the sun as is normally the case while the instrumentation was protected from the sun. The initial work was done by periodically observing a pair of orthogonally mounted, one-second precision levels aligned on top of the pedestal. As this method required constant attendance, it was soon replaced by the use of a Tilt Angle Transducer. This instrument made it possible to monitor the pedestal for several days at a time with minimal attendance. Because some difficulty was experienced with the thermal stability of its circuitry, the author returned to the use of precision levels. This equipment was expanded so that level indications were recorded on film by means of time-lapse photography. The time of each observation and the temperature of the levels were also made part of the record. Photographs were made every ten minutes. In most cases only one record per hour was later reduced, but the intermediate records were always available for study during the periods of rapid motion. This equipment was designed to operate for periods of one week without the need for servicing.

During the pedestal tilt measurements, the Tilt Angle Transducer and the precision levels were repeatedly checked against each other by duplicating data runs with each of the instruments. Good agreement was observed. The Tilt Angle Transducer is very fast in responding to a change of conditions but re-

TABLE 4

Emulsion creep: number of plates: 26				
standard error:	$\bar{s}_e$	1.54		
	s	0.21		
Reseau images:				
setting error:	$\bar{s}$	2.43		
	s	0.55		
	SDM	1.21		
		BC1000	BC600	BC300
number of plates	N	57	8	62
Star images:				
setting error:	$\bar{s}$	3.29	3.67	3.09
	s	0.64	0.54	0.53
	SDM	1.64	1.83	1.54
Orientation:				
standard error:	$\bar{s}_o$	5.32	4.56	3.76
	s	0.61	0.68	0.78
arc sec:	$\bar{s}_0$	1.″06	1.″50	2.″45
Flash images:				
setting error:	$\bar{s}$	4.10	4.18	4.19
	s	0.65	0.78	0.86
	SDM	2.05	2.09	2.09

quires good temperature control of its environment to do its best work. The precision levels were very reliable in operation but showed a frictional lag of about one second of arc when following very slow changes in tilt.

CLOSURE

The results of the BACAR effort to date serve to indicate the magnitude and direction for future investigations. The major amount of future effort is to be expended in reducing those factors which were found to be limiting the accuracy of the Ballistic Camera Systems.

A total of 127 Ballistic Camera plates were evaluated to determine the operational capability of the Ballistic Camera system as used on the evaluation program of October 1962. The plates were evaluated for the factors of:

1. Emulsion creep——setting error on images and standard error of the emulsion calibration adjustment. The emulsion calibration was performed on only 26 plates.
2. Setting error on star images.
3. Setting error on flash data point images.
4. Standard error of unit weight for camera orientation.

Except for emulsion creep, the data were evaluated independently for each type of camera system. No attempt was made to separate triangulation error into components for the individual cameras, or camera types.

The following definitions are used in the evaluation:

- $\bar{s}$—R.m.s. setting error (standard deviation of one setting) computed as the root mean square of the individual setting errors for all the plates considered.
- s—Standard deviation of the individual setting errors about the r.m.s. value.
- *SDM*—Standard deviation of the mean for the setting error. Since the value of each measurement is the average of 4 readings, this value is determined by $\bar{s}$ divided by $\sqrt{4}$.
- $\bar{s}_e$—The r.m.s. standard error of unit weight from the emulsion creep adjustment computed from the reseau residuals following a 2nd degree calibration fit.
- $\bar{s}_o$—The r.m.s. standard error of unit weight for the orientation adjustment of the plates. Computed as a root mean square; since each plate had sufficient degrees of freedom for a satisfactory orientation and is therefore considered as a separate unit.
- $\bar{s}_t$—The pooled standard error of unit weight for triangulation of all images on all plates.

The results are shown in Table 4 where all the values are in microns unless indicated otherwise.

See announcement of International Congress on page 319.