*Design Considerations in Range Instrumentation**

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ABSTRACT: *Ballistic cameras are typical of an important class of range instruments, and are presently used as calibration standards, for positional measurements, and for long-range geodetic surveys. Considerations significant to the design of ballistic cameras are discussed, and examples of two optical systems are presented. The trend toward higher performance leads the designer to consider longer focal-length systems: an upper limit of two to three meters is probable. Further improvements and new developments in ballistic camera design are reviewed briefly.*

RANGE instrumentation includes devices giving performance data on the object being tested on a range. Accordingly, range instrumentation devices reveal the location of an object, its velocity, acceleration, direction of motion, spatial attitude, what is happening in its immediate environment, how its propulsion system is operating, the influence of external forces, and so on. In these terms, the object being tested may be a ship, automobile, aircraft, a missile on the Atlantic Missile Range, or a research rocket in a hypervelocity tunnel. For purposes of discussion, we shall limit our attention to design considerations of the particular class of instrumentation which includes optical devices used to obtain performance data on test missile vehicles.

For convenience, optical range instrumentation is often classified by the type of information sought. Documentary, engineering sequential, tracking, calibration, and positional objectives are served by different types of optical range instrumentation. Confining attention once more, let us consider the ballistic cameras which have particular value in providing calibration data, positional information, and data important for long-range geodetic surveys.

We may consider first the purposes served by ballistic cameras and then the design considerations which support those purposes. A ballistic camera is normally operated on the ground. It is a fixed camera. Once it is properly oriented, it hopefully will not move or be moved during the exposure cycle. Furthermore, we say it yields calibration data in the sense that the information collected can be used to correct, or calibrate, information collected by range instruments operating in other frequency domains, or at other data rates. Ballistic camera exposures are normally recorded on photographic emulsion supported on glass plates. A distinguishing feature of ballistic camera photography is that the source is normally of point-like quality, and not resolved in the usual sense.

In the early days ballistic cameras were mainly positional instruments. Without great difficulty, velocity and acceleration information was also obtained. In the last decade, the ballistic camera has become a calibration device. Its value in this role is related to the low bias of ballistic cameras, the increasing value of the larger number of data points obtained by electronic instruments, and the more nearly "all-weather" capability of these electronic devices. In general, the calibration of many of these electronic devices is dependent on the low instrumental bias, or low systematic error characteristic of well-designed ballistic cameras. Without proper calibration, data obtained by these devices is of limited usefulness and meaning.

For all the apparent simplicity of the product, the design of a ballistic camera usually involves a compromise among complex parameters. On the one hand, the camera will be operated in a fixed position; it will be protected from wind and thermal disturbances, and exposures will be made on a special emulsion supported by stable, flat plate glass. The camera consists of a lens and cone, plateholder, shutter and mount. Nothing apparently could be simpler in design, construction, or operation. On the other hand, consider what has been happening on the ranges

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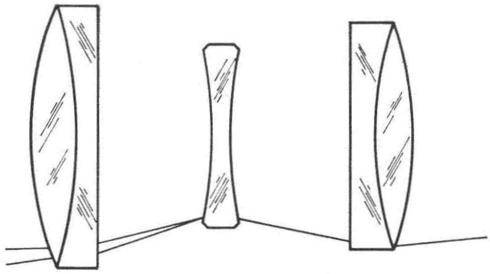

FIG. 1. 1,200 mm., f/5 pentac objective design.

to complicate matters. Missile velocities are increasing; information is needed over longer ranges and trajectories, and the total number of vehicles being tested is increasing to the point where timely data reduction is important and tougher to get.

Some of the basic characteristics to be accounted for in the design of ballistic cameras include the following: Angles in object-space will be correctly reproduced in image-space. Elements of interior orientation can be calibrated or measured with an extremely low error. The accuracy of angular position of an object is a function of focal-length and how well the image is measured. The longer the focal-length, and the better the measurement in image-space, the better the accuracy of the direction to the object will be.

Short focal-length ballistic cameras certainly were suitable for low velocity vehicles. It was logical to modify existing optical intruments in meeting these needs. The choice generally was an aerial camera objective. Indeed, the use of modified aerial camera objectives became so common that the limitations of this choice at a time when the vehicle moves at a velocity many times faster than aircraft often has gone unrecognized. The selection of an objective on grounds of availability, low radial distortion, and convenient focal-length has not been universally rewarding.

A current approach to the design of a qualified ballistic camera objective takes into account many factors. Chief among these in the selection of an optical system design that ensures the formation of symmetrical images independent of object color, exposure-time, or f-stop. Image quality is of singular importance; one goal in the system design is to ensure that the photographic image-center of density corresponds to the optical image-center of density. The demands on image quality necessarily prohibits comatic flare, lateral color, lateral secondary color, vignetting, and field curvature, but may admit small amounts of spherical aberration, astigmatism, and longitudinal secondary color. Tangential distortion, usually a function of manufacturing and assembly, is extremely tough to deal with in ballistic camera applications.

Specifying focal-length involves estimating the angular accuracy requirements of the system, the user's plate measurement capability, the film manufacturer's success in producing a highly stable emulsion, and the film processors' finesse in producing dense measurable images where they were formed optically. Not long ago, the case arose in which a design was required which was to be limited only by factors completely outside the designer's and manufacturer's control. These external factors, headed mainly by angular deviations due to atmospheric seeing, indicated that the angular limit of a system was variable but probably seldom exceeded one part in a million or about 0.2 arc second. Taking emulsions and processing instabilities, measurements and the other factors into consideration, a focal-length of at least two meters was deduced. This was predicted on the assumption that total image and measurement errors could be kept under two microns. For the more usual case of seeing imperfections, a fully refractive system of 1,200 mm. focal-length was evolved in a symmetrical form free of radial distortion. This design is illustrated in Figure 1.

Determining the aperture can be a stickier problem. Investigation reveals that the angular deviations due to atmospheric seeing behave in such a way that the effects can partly be averaged out. Astronomers have accomplished this through their very long-time exposures. Another way of doing it—since missile tests don't permit very long-time exposures—is to average out the effects spatially. The techniques require a wide aperture diameter. A compromise is sought between the smallest aperture diameter we can get away with and still attain the spatial averaging required in angular terms, and the minimum aperture area necessary to collect the energy emitted at the vehicle which is often hundreds of miles distant. The compromise also involves how much aperture the dollar budget will stand, the design feasibility, and perhaps weight and size when portability is a factor. In the 2 meter focal-length case cited above, not only was an f/3 indicated for seeing reasons, but it offered ample light collecting area, a feasible design, appeared to satisfy economic considerations, and appears to be about as large as one could go and still offer mobility.

Having arrived at a suitable focal-length and f/number, one may then consider image characteristics, the spectral band within which images are formed, radial distortion, and image aberrations. For effective ballistic photogrammetry, the image must be circularly symmetrical and uniformly dense. In the design of the systems cited above, an optical image diameter of 10 microns was sought and attained. Arguments continue about the merits of resolution criteria. It applies to aerial photography, and aerial cameras have been modified for use in ballistic application. Frequently the term still crops up in procurement specifications. But the ballistic camera is not primarily designed to resolve detail. The target is a distant point source, and reference orientation stars are distant point sources. We do insist on circularly symmetrical, dense images of about 10 microns diameter.

Perhaps now the optical design can be completed. Which one is chosen? Generally, it is that with the fewest elements. Two big considerations are involved: cost and accuracy. In a long focal-length, large aperture camera, the cost goes up rapidly with each added optical element. One must consider not only the cost of raw glass, but grinding, polishing, figuring, testing, holding, mounting, assembly tests, component tests, lens tests, test fixtures, and tools. Furthermore, the final capability of the system to deliver accurate results is a function of the accuracy of the parts or elements. The more elements, the tougher the job of keeping them where they must be to perform accurately. Simpliticy pays off. There are cases where this rule cannot apply, and there are the expedient cases where it is violated. But it is a good rule and worth understanding.

An example of a simple but well-qualified design is provided by a highly refined version of the Baker-flatfield Schmidt, consisting mainly of a primary mirror, a secondary mirror—both nearly spherical—and a field flattener, illustrated by Figure 2. This design exhibits nearly all image quality characteristics desired in a long focal-length ballistic camera objective; in addition, it offers the opportunity for metric photographic data to be collected with an accuracy limited only by external natural effects wholly outside the control of the designer.

Next, one might consider the matter of ballistic camera shutters, optical filters, and the camera mount. Filters generally are employed in the long focal-length ballistic cameras to control illumination coming through the optical system. Iris diaphragms are effective for this purpose, but have the unfortunate side effect of reducing the effective aperture diameter and hence compromise the design objective of averaging out seeing deviations. Neutral density filters might be designed to fit near the focal-plane; local irregularities then are less serious.

Shutters for large aperture ballistic cameras are truthfully a major problem. One of the most promising mechanical solutions appears to be a refined version of the louvre or "venetian-blind." One is constrained severely in shutter form and location by the necessity for shuttering all parts of the image-plane simultaneously, and for avoiding image degradation. In these terms, one is sometimes forced into an external shutter of very wide aperture.

Ballistic camera mount designs are sometimes overlooked. Convention has generally

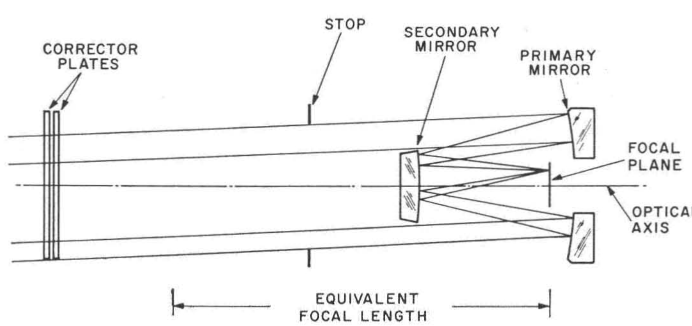

FIG. 2. Illustration of elements of 2,000 mm. focal length, f/3, T/4.2 ballistic camera objective; field is slightly over 5°×5°.

Features: Largest aperture for least cost, excellent chomatic correction, symmetrical off-axis imagery, very low distortion.

favored a fixed alt-azimuth mount for pointing and holding the camera. In many cases this is good enough. What is generally overlooked is that when a fixed alt-azimuth mount is chosen, one is forced to employ a metering type shutter. On the other hand, the shutter problem is simplified when the mount is polar and driven at earth rate; one then keeps track of angular mount motion. Mount design, then, is related to shutter complexity, timekeeping apparatus, the type of target being photographed, and data reduction capabilities.

The designer faces practical questions of size, weight, delivery, and cost. Portability has been a desirable attribute, to enable meeting the requirements of rapidly changing range operations. Even at focal lengths of 2,000 mm, and apertures approaching a meter, portability can be obtained, although its value and merit must be balanced carefully against hazards of shipment and small benefits of minor relocation. For the very long focal-length instruments, substantially new installation facilities are needed, both to get the camera above ground level seeing disturbances and to provide necessary stable support. Delivery is only partly within the control of the designer, to the extent that the choice of optical materials is from available stock. It is increasingly difficult to produce the optical systems having the superior qualifications now required in much less than two years. These are hard facts to accept and often discouraging. Perhaps acceptance of this view by potential users will assist the orderly programming of requirements. We have not completely overlooked cost; cost probably deserves as much careful thought as the technical design, but infrequently gets it. Modified aerial cameras of short focal-length can be obtained for about twice the cost of a first-order theodolite and up. This includes the lens, camera, modified theodolite mount, and various accessories. Ballistic cameras based on modified aerial and aerial telephoto assemblies are still produced in this country. In these cases, a trade-off has been employed which sacrifices performance in the interest of reducing cost. Where performance is important—and let there be no mistake, the consequences of sloppy performance are tremendously more costly in the long run—then initial instrumentation costs are high. It's probably a fair estimate that costs go up at a slightly higher rate than instrumental capabilities. On that account, where angular accuracies of a very few micro radians are considered, the cost is probably increased by an order of magnitude over the modified aerial cameras.

What of the future in range instrumentation? Where do we go from here? I think we shall reach a limit on focal-length at 2–3 meters; this is a big instrument. I think there is a good case for design improvements through reducing size and weight; the operating and transportation personnel should welcome this. One of the techniques applicable might be the use of lightweight reflecting optical elements; the weight of a primary mirror can be cut nearly in half, and some aspects of performance improved by use of lightweight construction. Reflective optics generally offer the most aperture per dollar. The technique may employ foamed quartz, honeycomb, sandwich, or just holes drilled in the back. Another technique for reducing size and weight is the application of solid optical systems, that is, the elimination of airspaces. In those solid systems built so far, the main problem has been a restricted field angle. But think of the tremendous value of an optical range instrument which is extremely compact and physically can't go out of alignment because there just isn't any place for the elements to shift.

Finally, rapid development in the field of optical masers points the way to a new family of range instruments of some elegance. One is being considered at this time which employs a laser operating in the visible spectrum. This one might yield spatial target position to an accuracy of two seconds of arc, fully competitive with ballistic cameras now in use. The particular merit in this system is that it's lightweight, portable, when properly filtered permits day or night operations, and delivers its output in real time, something now lacking in ballistic cameras.