A Design and Operational Philosophy for an Ultra-Precision Tracking Mount System for a Missile Test Range

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Test-range requirements for a ground-based instrument station which will combine optical, photographic, television, photoelectric and electronic event-observation and recording devices carried on a servo-driven tracking mount of theodolite accuracy are discussed. The system will obtain missile-performance data and produce records in forms suitable for use in automated data-processing systems. The tracking-mount configuration and design considerations are described in detail.

A GUIDED-MISSILE test range is essentially an outdoor or free-flight wind tunnel, instrumented to obtain quantitative data on the performance of developmental missiles and weapon system components.

The data required in guided-missile tests may be roughly divided into six types: (1) trajectory (space-position vs. time), (2) velocity, acceleration and drag coefficients, (3) attitude (pitch, yaw and roll with respect to the trajectory, and spin), (4) component functions, (5) relative-trajectory (booster separation, miss distance, multiple missiles or targets) and (6) internal functions.

To obtain these data, four classes of instrumentation are used:

1. Cameras or other recording instruments mounted within the missiles or aircraft. These instruments must be recovered to obtain the data.

2. Telemetering, which transmits data from internal instruments.

3. Electronic ground-instrumentation systems. These must be capable of obtaining line-of-sight angles, slant-range-to-target, or target radial velocity data, and are used to obtain position and sometimes velocity and acceleration information.

4. Optical ground instrumentation.

The related and interdependent roles played by optical and electronic ground-instrumentation may be considered by briefly examining five aspects of data acquisition as they affect electronic and optical systems.

1. Information Rate. This is the product of "bits-per-sample" and sampling rate. Electronic systems characteristically handle only one "bit" of information per sample, whereas an optical system that resolves 30 lines/mm is capable of presenting $1\frac{3}{4}$ million "bits" simultaneously on a 2-in. diameter image field. The electronic system may be capable of transmitting or recording a million or more samples per second while the optical images can be recorded on film at sampling (frame) rates limited to a few hundred per second. This can be illustrated by the television process wherein an optical system forms an image containing all the information in a scene at a given instant and an electronic system "scans" the image to pick off and transmit individual "bits" sequentially. The electronic sampling rate must be high enough to handle the total number of bits in the image in one interframe time interval if the optical and electronic systems are to have the same information rate. The large number of "bits-per-sample" characteristic of image-forming systems renders them capable of obtaining attitude or multiple target data.

2. Real-Time Data vs. Stored Data. Electronic systems generally produce data in the form of analogue electrical signals which can be recorded on magnetic tape, and processed, displayed and plotted all in a small fraction of a second, thereby making information available for immediate use in test-control and range-safety operations. Film recording, usually employed as the recording medium in optical systems, fails to provide real-time data in that the film must be processed and the data read off and translated into punch cards or magnetic tape before it is ready for further processing.

*3. "Augmented" vs. "Unaugmented" Modes of Observation.** Among electronic systems only skin-tracking radar is capable of tracking missiles without the aid of a transmitter or transponder in the missile. Beacon-tracking radars and all other electronic systems are "augmented," i.e., completely dependent on radiation from the target. Developmental missiles are frequently equipped with telemetering transmitters whose signals may be used by some ground-based electronic gear. Optical systems, working in the infrared, visible or ultraviolet portions of the spectrum, are capable of "unaugmented" operation and do not require any use of the radio spectrum. This capability permits coverage of small or multiple missiles incapable of carrying transmitters and also makes it possible to track targets during enforced "radio-silence" providing visibility conditions are not adverse due to clouds or nighttime.

4. Mount Vibration. Ground-based electronic angle- and distance-measuring equipment that operates without moving parts in the antenna systems obviously is not subjected to vibration. Vibration originating in azimuth and elevation power-drive elements and mechanical scanners in tracking radar systems does not deteriorate the data obtained. In optical systems, however, vibration originating in the mount power drives, in camera mechanisms, or even vibration set up by wind in resonant lens-support structures, can result in significant image deterioration and consequent impairment or loss of data.

5. Target Acquisition. The process of finding and bringing an instrument to bear on a hard-to-see, fast-moving target has been defined as "target acquisition." Some electronic systems are omnidirectional and will pick up any target within their range; and tracking radars are frequently provided with automatic-search devices. On the other hand, operators of long-focal-length narrow-field optical systems may encounter great difficulty in finding the target without assistance from instrument-positioning or target-designation systems.

Optical instruments in current use have been developed to meet specific data acquisition requirements brought about by the rapid expansion of the guided-missile art. As a result, none of the available instruments is capable of collecting all five types of external data, and it is customary to use cinetheodolites, high-speed tracking mounts, and tracking telescopes to obtain photographic coverage of a single test. Additional instrumentation for launching studies and real-time coverage is also required. It is apparent that we need a single-unit, integrated instrument system which

* The frequently misused terms, "active" and "passive," are not applicable here since they properly refer to the necessity for, or independence of, the emission of acoustic or electromagnetic energy by a detecting, seeking or tracking device. We are here concerned with requirements for emission, by the target, of energy in specified portions of the spectrum.

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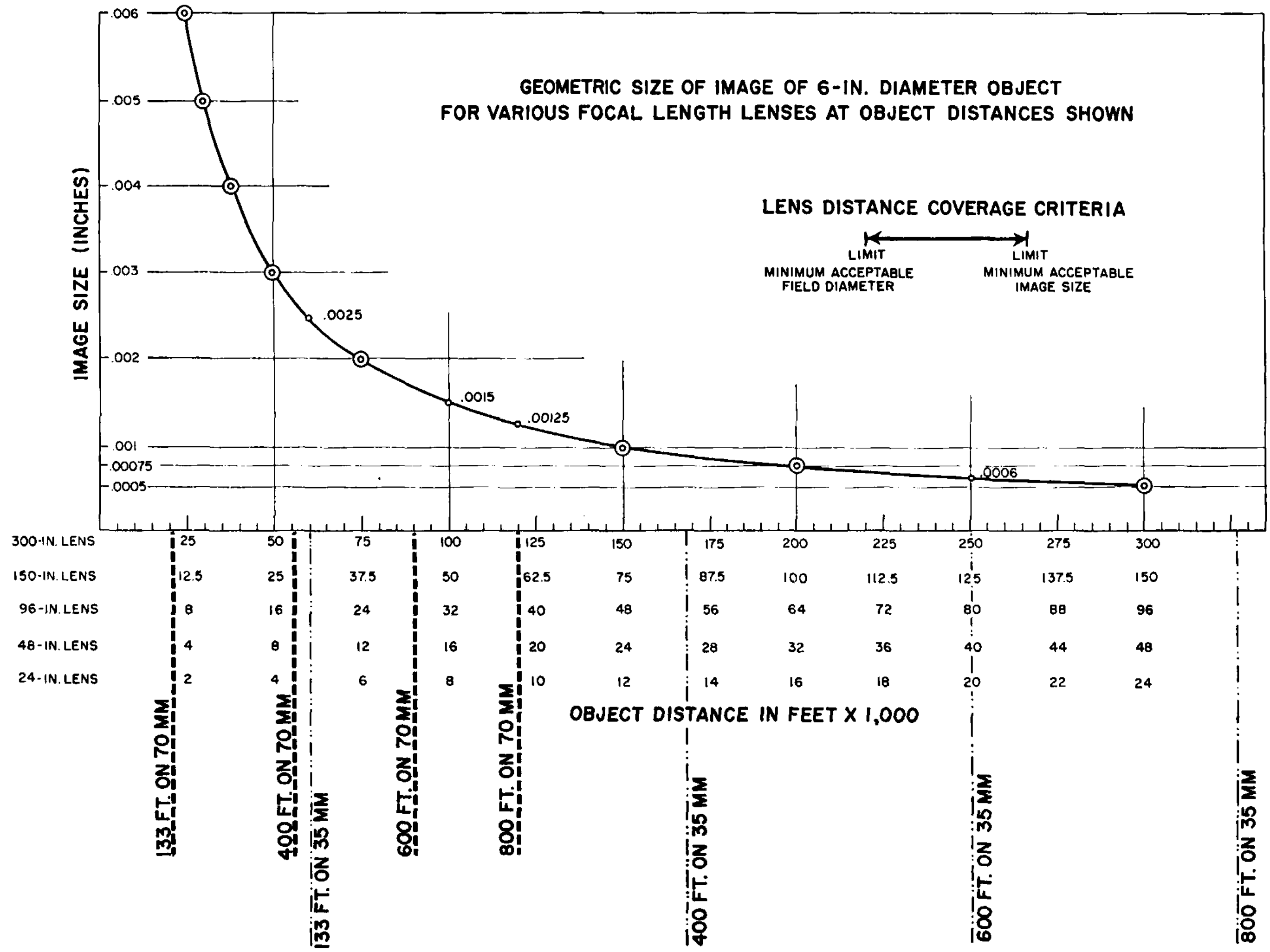

Fig. 1. Lens selection graph for long-range missile tracking instruments. Limits of 0.00075-in. image width and 600-ft diameter field have been chosen empirically for instrument design purposes at Naval Ordnance Test Station. Dotted lines show minimum distance for indicated coverage diameter in object space. - - - - - - - 70mm frame = 2-in. diameter field; —· · —· —· · — 35mm frame = 0.720-in. diameter field.

will combine the functions of cinetheodolites, high-speed mounts and tracking telescopes, to provide more accurate data, provide real-time data not now available from these instruments, and, through the employment of electronic accessory equipment, produce recorded data in a form suitable for direct entry into a fully automated data processing system.

The Tracking Instrument Mount or TIM System, now under development by the Navy's Bureau of Ordnance, is expected to fulfill these requirements.

Major Considerations in Design of Tracking Mount

The size of the tracking mount is determined by the event-observing gear to be carried, in this instance the lenses. It is intended that large long-focal-length optical systems will be used both for photography and in conjunction with automatic electronic image-scanning systems that will provide digital tracking-error data recorded on magnetic tape. Television cameras behind long-focal-length optical systems may be used in closed-loop systems for remote group-viewing of missiles in flight by test engineers, range safety officers, and others.

Since it is expected that the electronic scanning systems and television cameras will have approximately the same resolution and sensitivity as fast films, we shall consider only the photographic problems in choosing the lenses to be used.

As a result of field experience we may establish the following lens criteria: for reliable trajectory and relative-trajectory data the minimum geometric or computed width of an acceptable image shall be 0.00075 in. In order to assure an acceptable number of frames containing images of both the missile and its target at intercept, and to cover dispersion patterns of multiple missiles, the field of view at the target must be at least 600 ft in diameter.

Reflectors or catadioptric-type lenses of long focal lengths can be produced to cover image fields up to 2 in. in diameter with relative ease, whereas larger fields are difficult to obtain because of the larger obscuration ratios and higher-order corrections which they require. By coincidence, a 70mm cine camera with a 2-in.-square frame is the largest camera which can be produced for use with standard film and be capable of frame rates up to 100/sec. It is required that the TIM System be capable of obtaining data on a 6-in.-diameter missile at all slant ranges between 10,000 and 100,000 ft and in addition meet the above criteria. As indicated in Fig. 1, several lens-camera combinations will be needed. For example, four 70mm cameras (2-in.-diameter field) equipped with lenses of 27-, 48-, 83- and 146-in. focal lengths, covering ranges of 9,000 ft to 20,250; 14,400 to 36,000; 24,900 to 62,250; and 42,800 to 109,500 ft respectively, would provide 10% margins and 50% overlapping coverage.

For attitude and component-function data and special documentary coverage, where maximum obtainable image sizes

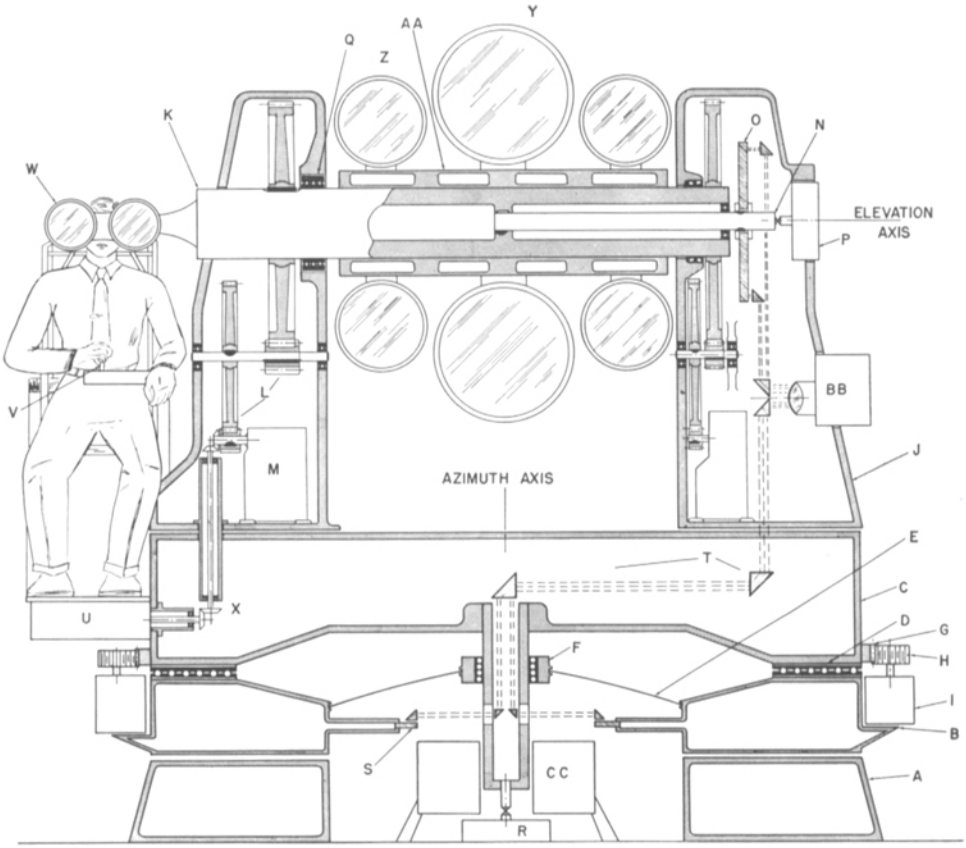

Fig. 2. Mechanical Schematic of TIM: A, base ring; B, upper base casting; C, azimuth rotating platform; D, azimuth thrust bearing; E, compliant diaphragm mounting for azimuth guide bearing; F, azimuth guide bearing; G, azimuth drive ring gear; H, azimuth drive pinion gear; I, azimuth drive motor and gearbox; J, elevation standard; K, elevation main shaft; L, elevation drive gearing; M, elevation drive motor and gearbox; N, elevation data shaft; O, elevation glass divided circle; P, elevation shaft-angle digitizer; Q, elevation bearings; R, azimuth shaft-angle digitizer; S, azimuth glass divided circle; T, circle reading optical train; U, operator's position; V, servo-drive control; W, operator's tracking telescope; X, operator's position drive gears; Y, 18-in. diameter telescope objective; AA, instrument supporting platform; BB, circle recording camera; CC, electrical slip-ring assembly.

are needed, and where the field of view may in some cases be as small as 60 ft in diameter, lenses with effective focal lengths up to 300 in. will be used. Relative apertures of T-10 have been found to be adequate for 1/1000-sec exposures with 4X filters on black-and-white film, and for 1/500-sec on color film. TIM lens systems will be designed for use with post-image magnification at two or more effective focal lengths, with the absolute aperture determined by the longest focal length. A typical lens system for TIM will be 12 to 18 in. in diameter, and $2\frac{1}{2}$ to 6 ft long. Although not all stations will be required to cover the entire range of distances within the instrument capability, it is probable that some mounts will be equipped with as many as six lenses (with effective focal lengths of 24 to 300 in.), two 35 mm and two 70mm cameras, and two electronic image-scanners. From this we conclude that the mount must have provision for mounting up to three optical systems above and three below the elevation main shaft (Fig. 2).

Considering the maximum payload or instrument complement indicated above, and the necessary provision for "dumping" the telescopes for forward and reverse sights, the requirements are about a $3\frac{1}{2}$-ft minimum clearance between the mount elevation standards, a 4-ft swing clearance below the elevation axis, and a load-carrying capacity on the elevation bearings (including the weight of the elevation main shaft and the instrument support structure) up to 4,000 lb. These dimensions and loads in the elevation assembly imply that the azimuth rotating platform will be approximately 8 ft in diameter, and that the entire structure rotating around the azimuth axis will weigh around 10,000 lb.

Data Accuracy Requirements

In order to meet data-accuracy requirements, design goals for the mount have been set at 2 to 3 sec of arc for azimuth and elevation axis-wobble, perpendicularity of the axes, structural deflections (caused by mechanical loading and thermal effects), accuracy in the divided circle and digitizer angle-measuring systems, and determination of mount mislevel and lens collimation.

It is felt that azimuth bearings or roller-paths of conventional configurations — balls or rollers running in steel races which are supported on, and subject to the constraints of, large castings or weldments many times more rigid than the races — cannot be expected to attain this accuracy consistently under range conditions. The azimuth bearing configuration proposed for TIM combines a thrust element, employing 2,000 to 3,000 small steel balls distributed in an annular space between upper (rotating) and lower (fixed) plane surfaces produced directly on the parent metal of the main castings or weldments, with a compliantly mounted guide bearing to provide only radial constraint without redundancy in determination of the axis of rotation. The elevation bearings, being spread approximately 5 ft, present a much simpler problem in attaining the desired accuracy, provided the elevation shaft is stiff enough. It is proposed that the TIM elevation main shaft will be a tube made of the same material as the major mount elements, be approximately 10 in. in diameter, and pass unbroken through both sets of standard bearings with both radial and longitudinal constraint on one end and only radial constraint on the other end.

To minimize vibrations and strains in the mount structure, which will be required to track at rates up to 60°/sec with momentary accelerations as high as three radians per second per second, the azimuth drive will be applied to the rotating member by four fixed motors operating in parallel and disposed at 90° intervals around the rotating platform — thus distributing and reducing the amplitude of stresses, balancing out radial forces on the guide bearing, and reducing the size and mass of rotating elements. If possible, a timing belt final drive will be used so that pure tangential driving forces will be applied to the azimuth rotating platform, metal-to-metal gear contact and localized high tooth pressures will be eliminated, lubrication and oil- or grease-tight housings and seals will be unnecessary, and the effects of manufacturing tolerances, wear, or departure of the large ring gear from true circularity will be minimized. (In a single-pinion-gear drive system, defects, wear, or distortion, in either the pinion gear of the 8-ft-diameter ring gear, resulting in as little as 0.0002-in. backlash, could cause significant vibration.)

Stresses originating in the elevation drive system will be distributed by using two parallel drives in the standards. This reduces the size of rotating elements and minimizes torsional stresses in the elevation shaft.

Materials used in the mount's main castings or weldments should be carefully selected for stability and vibration-damping properties, and dead-annealed before final machining to assure that initial accuracy built into the mount can be maintained over a long period of field operation.

There should be the tightest possible angular coupling between the optical system lines-of-sight and the elevation-glass divided circle and shaft-angle digitizer. A coaxial data shaft, located inside the tubular elevation axis main shaft and free from torsional and bending loads, will connect the elevation divided circle, shaft angle digitizer and the elevation synchro transmitter system directly to the main shaft in the center of the payload area.

Three independent systems for measuring and recording azimuth and elevation angles will be provided in the TIM mount. First, the readings of coded, graduated glass circles on the azimuth and elevation axes will be recorded on film with strobe lamps. The film records will be assessed in semiautomatic reading machines capable of reading the angles to a least count of 0.001 degree. Tracking-error corrections to these records will be read from the long-focal-length target-camera films. Second, gear-driven synchros and resolvers will supply continuous electrical analog signals (uncorrected for tracking errors) for real-time applications. These signals will be used to operate plotting boards, as angular position references in master-slave operation and in positioning the mount in response to information received from target-acquisition systems. Third, shaft angle digitizers will provide precision digital azimuth and elevation-angle records on magnetic tape. These records will be combined with tracking error corrections on magnetic tape, obtained from the electronic image-scanning devices mentioned earlier, for direct entry into a fully automated data-reduction system.

The azimuth and elevation servo-drive systems will respond to signals originating in the operator's control element, to position or rate data received from preset programming devices or target-acquisition systems or to error voltage signals generated in the electronic image-scanning systems, thus providing local, slave, or automatic-tracking modes, respectively.

The operator will always have override control when in slave or automatic-tracking modes.

Because of high peak personnel loads implicit in test-range operation, the TIM must be manned by a single operator. Maximum utilization of the operator's abilities will be facilitated by the application of human engineering techniques to the design of the operator's position and controls. The electronic servo-control system will be designed for maximum flexibility in the introduction of various transfer functions to obtain optimum smoothness and accuracy of tracking under all range conditions.

It has been found that random momentary obscurations in the human eye cause an operator to lose sight of distant targets when the image approaches the vanishing point. The operator's telescope on TIM will be a binocular-type to assist the operator in tracking to maximum ranges.

TIM systems will be installed on specially constructed towers and protected by power-driven astrodome-type enclosures, especially at down-range sites, to provide extended range coverage. The TIM System, because of the integrated design employing both optical and electronic means for obtaining data, will provide great flexibility in coverage, real-time data and pictorial coverage, and stored-data in forms compatible with the highly automated data-processing systems now being developed.

The benefits to be derived from this system, which include more accurate test data than are presently attainable, more rapid delivery of test results to weapons development agencies, significant improvements in instrument dependability, and economies effected in range operations and data processing, are expected to make the TIM a basic ground instrumentation system for guided-missile test ranges.

Discussion

A. M. Erickson (*Naval Ordnance Laboratory, White Oak, Md.*): Is it correct that the mount is capable of 50 or 60 degrees per second tracking rate?

Mr. Clemente: That is one of the requirements.

Lincoln L. Endelman (*Convair Astronautics, Cocoa Beach, Fla.*): If this isn't classified, approximately how soon do you expect to have some of these in operation?

Mr. Clemente (*by mail*): The American Machine and Foundry Co. is currently working on the design of TIM under a Bureau of Ordnance contract for complete drawings and specifications for prototype production. The design is scheduled for completion in March 1959, with actual construction of prototypes to follow.

At the Convention Mr. Clemente advised: It occurs to me that much of the material that was discussed previously this afternoon had to do with large missiles, or other objects at distances up to several hundred miles. I think it should be made clear that the mount discussed in this paper is intended primarily to handle up to distances of something less than 100 miles, and that many of the missiles may be only the 6-in. diameter missile that we took as a standard in determining lenses.