Flying Camera Stations

By FLOYD A. KINDER

This type of instrumentation is based upon the principle of determining aircraft positions and attitude by photographing surveyed ground markers with one aerial camera. To obtain attitude, trajectory and documentary data of missiles launched from aircraft at high altitudes an Airborne Cinetheodolite based upon this principle has been proposed. Factors affecting the accuracy are presented.

THE CONCEPT of a flying camera station is based upon the principle of determining aircraft attitude and position by photographing surveyed ground markers (Fig. 1). The advantage of this method is that a complete solution is obtained from one photograph, without recourse to ground instrumentation. Although various applications using analog data-reduction methods have been in use for some time, only recently have satisfactory analytical solutions been made possible — a situation resulting chiefly from the advent of high-speed electronic computers.

Basic Solution

The analytical solution in use at the Naval Ordnance Test Station is a combination of various solutions* incorporated into one program for the IBM 701 Computer. This program first makes preliminary corrections for lens distortion, film shrinkage and rotation of the film when read in the computer. The X, Y, Z camera position is then determined from four markers that are assumed to be at the same elevation. An iterative solution is used to correct for variation in elevation between the ground markers and for atmospheric refraction until the successive changes in the X, Y, Z position are negligible. The attitude is then computed. From this position-and-attitude determination a least-squares solution, which uses up to 18 ground markers per film frame, recomputes the position and attitude and indicates the accuracy of the completed solution from the residuals. This program also has an additional feature which computes the film-reading accuracy and eliminates any marker readings exceeding a set variance before recomputing both position and attitude.

The solution can be considered a ratio-type problem, with the rear node of the lens separating the interior and exterior orientation. The interior orientation is determined by the calibrated focal length and the location of the principal point. Errors in interior orientation could be caused by (1) changes in focal length, (2) lens distortion, (3) film shrinkage and emulsion creep and (4) movement of fiducial marks. Since the accuracy of the solution depends on the cone of rays from the rear node to the film plate having the same angular relationships as the cone of rays from the ground to the rear node, a camera with a rigid inner orientation is required.

Several cartographic-type cameras (developed for mapping) have an inner structure that keeps the lens rigid with respect to the focal plane, as well as a between-the-lens shutter and a lens calibrated for distortion. In a calibrated cartographic plate-camera, the net inner orientation error can be held to around 0.01 mm on the film plane, which gives an idea of the magnitude of errors permitted in the exterior orientation. For example, a displacement of 0.01 mm on the film plane of a camera with a 6-in. effective-focal-length lens at 10,000 ft is equivalent to 0.7 ft on the ground. This means that in flights below 10,000 ft, the survey would need to be at least second-order if the survey errors were to be smaller by one magnitude than the camera errors.

Another factor to consider in the exterior orientation is the configuration of the markers themselves. The ideal would be to have the four principal markers at the corners of the field-of-view of a 90° lens in order to have a good triangulation angle. Considerable variation from this ideal can be allowed without unduly affecting the accuracy, as can be seen from the typical examples in Fig. 2. This factor probably accounts for most of the variation in standard deviation, if the film reading accuracy has been constant.

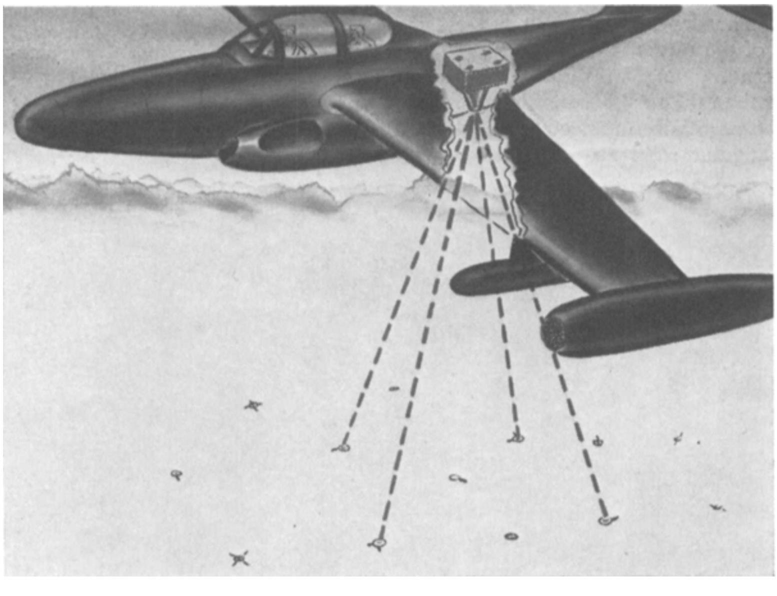
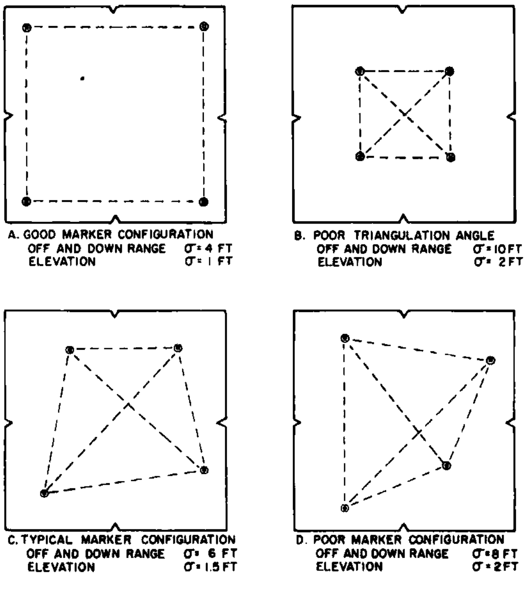


Fig. 1. Basic aerial camera instrumentation for determining position and attitude of an aerial camera by photographing surveyed ground markers. (Official U.S. Navy Photo)



A. GOOD MARKER CONFIGURATION
OFF AND DOWN RANGE $\sigma = 4$ FT
ELEVATION $\sigma = 1$ FT

B. POOR TRIANGULATION ANGLE
OFF AND DOWN RANGE $\sigma = 10$ FT
ELEVATION $\sigma = 2$ FT

C. TYPICAL MARKER CONFIGURATION
OFF AND DOWN RANGE $\sigma = 6$ FT
ELEVATION $\sigma = 1.5$ FT

D. POOR MARKER CONFIGURATION
OFF AND DOWN RANGE $\sigma = 8$ FT
ELEVATION $\sigma = 2$ FT

Fig. 2. Typical effect of marker configuration on standard deviation of position. Test made at 15,000-ft altitude using RC-7 camera with 60° field-of-view.

Presented on May 2, 1957, at the Society's Convention at Washington, D.C., by Floyd A. Kinder, Test Dept., U.S. Naval Ordnance Test Station, China Lake, Calif.

(This paper was received on May 2, 1957.)

* Otto Neall Strand, "Mathematical methods used to determine the position and attitude of an aerial camera," (NAVORD Report 5333, NOTS 1585), unclassified, NOTS, March 1956.

The total effect of both internal and external (atmospheric refraction) orientation errors and poor marker configuration is to reduce the accuracy of the solution. The least-squares solution reduces only the effect of random errors. Any bias in the camera calibration or in other corrections results in a constant bias in the answer.

Test Results

Flight tests to evaluate the accuracy of the solution were made, using an RC-7 automatic plate-camera. This involved four flights at two different altitudes while using the same ground markers. Two of the flights were made at 10,000 ft with a 4-in. Aviogon lens (90° field-of-view), and two at 15,000 ft with a 6-in. Aviotar lens (60° field-of-view).

While the RC-7 aerial camera was photographing the ground markers, six Askania cinetheodolites were photographing the aircraft from the ground. The time of operation of the aerial camera and Askanias was transmitted by radio link and recorded on an oscillograph. As the aerial camera was not synchronized with the Askanias, the position data were interpolated. If the airplane were moving at other than a linear rate in a constant direction, this would be a source of additional error. Figures 3 and 4 show the test results. The center lines, representing the airplane position points as determined by the Askanias, are the standard, while the plotted points are the positions as obtained with the RC-7 aerial camera.

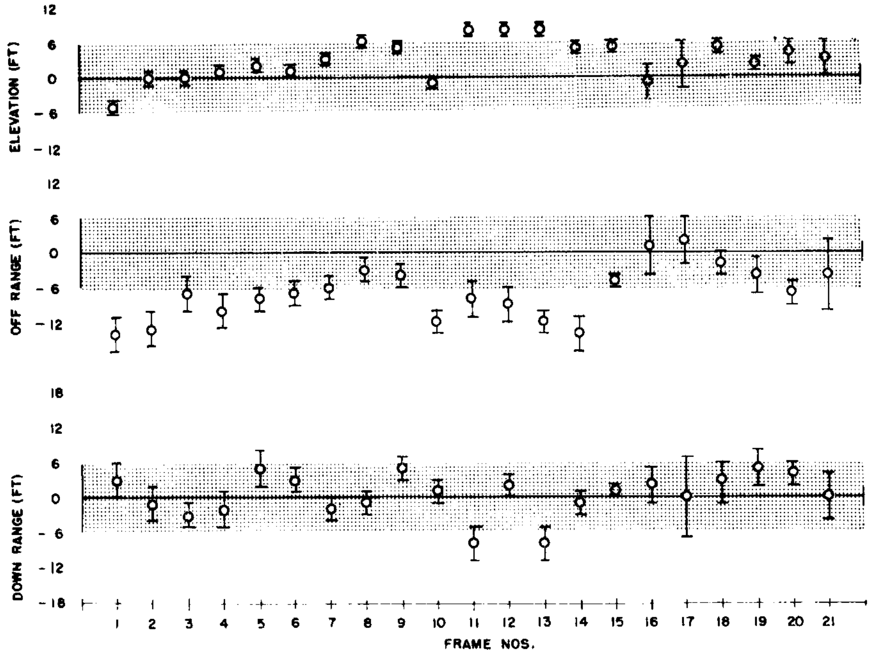


Fig. 3. Difference between Askania and aerial camera data at 10,000-ft altitude. Wild RC-7 aerial camera with 4-in. effective-focal-length lens, 90° field-of-view. ɸ =RC-7 data, the bars indicating its standard deviation. Shaded area is standard Askania deviation.

These results agree favorably with the accuracy expected from residuals of the RC-7 least-squares solution standard deviation computation. The average standard deviation of the RC-7, using the 4-in. lens (90° field-of-view), was approximately three feet in off-range and down-range and one foot in elevation, which was half the standard deviation when the 6-in. lens (60° field-of-view) was used. Part of the larger standard deviation of the 6-in. lens was due to the increased height — 15,000 ft compared to 10,000 ft — using the 4-in. lens, and the rest was probably due to the smaller triangulation angle.

Tests with a T-11 cartographic film camera, having a 6-in. lens and 90° field-of-view, under the same conditions had approximately the same standard

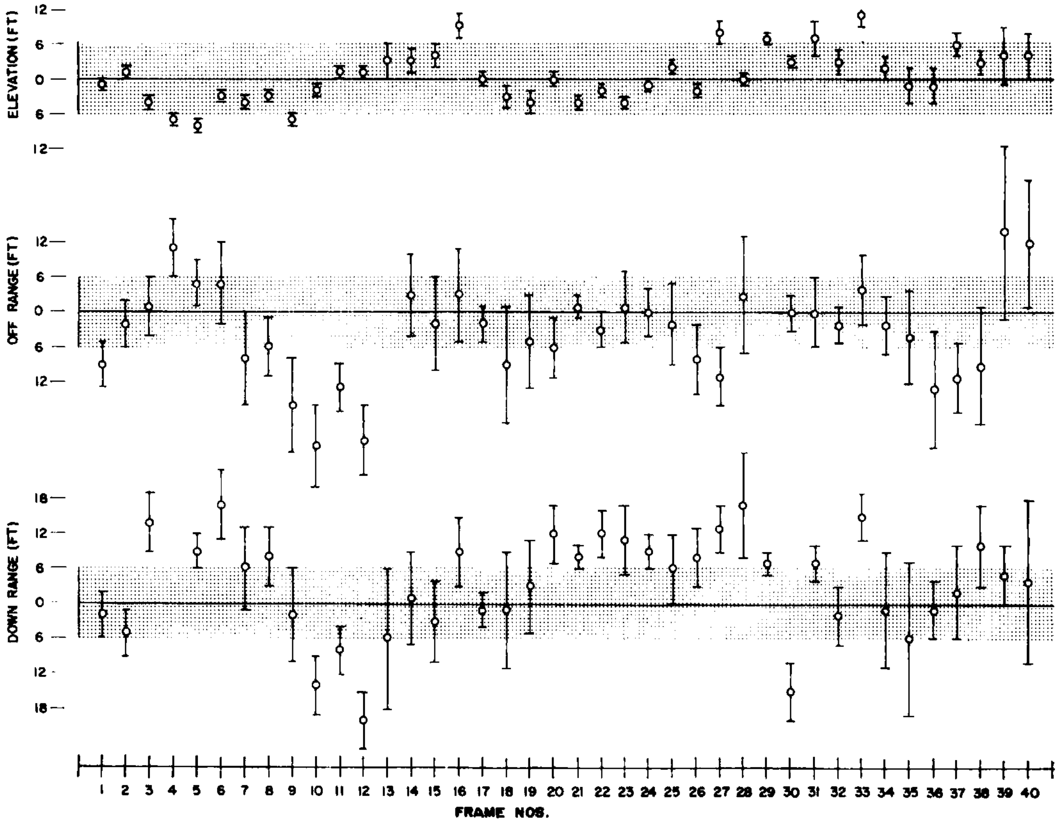


Fig. 4. Difference between Askania and aerial camera data at 15,000-ft altitude. Wild RC-7 aerial camera with 6-in. effective-focal-length lens, 90° field-of-view. ɸ = aerial camera data. Bars indicate standard deviation. Shaded area is standard Askania deviation.

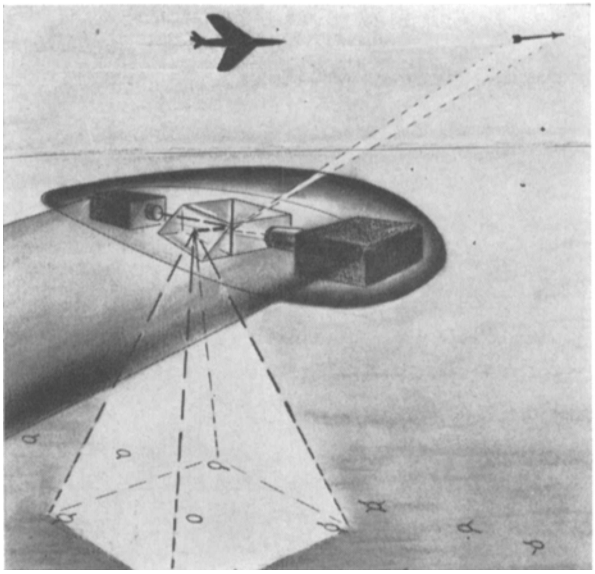


Fig. 5. Principle of airborne cinetheodolite: The angle from the tracking camera to the missile is determined by the other camera photographing the ground markers through a common tracking mirror. (Official U.S. Navy Photo)

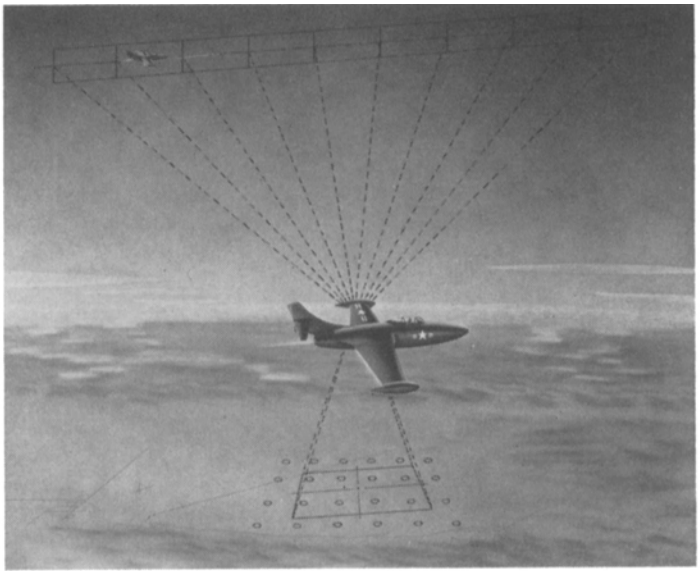


Fig. 6. Flying camera station carrying bank of fixed cameras in wing or belly pod to obtain missile attitude and trajectory data. Position and attitude of flying camera station are determined by an aerial camera photographing surveyed ground markers. (Official U.S. Navy Photo)

deviation as obtained with the RC-7 plate-camera using the 4-in. lens. The least-squares solution reduces the effect of the larger random errors in film, thus achieving almost the same accuracy as obtainable with plates, for the same accuracy in measurement. As the film is larger — 9 by 9-in., compared with 5½ by 5½-in. plates — the residual errors do not have as great effect upon the solution because of the increased scale.

Attitude Accuracy

Methods now being used to determine aircraft attitude are not nearly accurate enough for use in checking this method. The standard deviations in attitude obtained in the above test were all close in accuracy to 1 min. of arc, which is much better than the attitude accuracy obtainable with ground cameras. The high accuracy of this method of determining attitude, together with the simplicity of operations, should meet most aircraft flight-test and instrument check requirements of this type.

Applications of Flying Camera Station

Aircraft Orientation: The first use for this method has been the determination of position and attitude of the airplane carrying the camera. Such information is needed in bombing tests, and in determination of rate of roll and measurement of the stall angle of the airplane, etc. For most tests, especially in jet aircraft, the camera can be fastened rigidly to the airframe if fast shutter speeds (1/500-sec or better) are used.

Airborne Cinetheodolite: Another use for this type of instrumentation has been proposed for solving the problem of obtaining attitude and roll data of air-launched missiles at high altitudes. Because of the long slant ranges required if ground-based instruments are used, it is often impossible to obtain attitude information and difficult to even record some of the images because of the limiting effect of atmospheric turbulence. To rectify this it is planned to build an airborne cinetheodolite based on the principle of determining position and attitude with a single aerial camera. Two 70mm cameras would be mounted in a pod facing each other (Fig. 5), with a tracking mirror mounted between them. One camera would have a long-focal-length lens for tracking the missile, while the other camera would have a short-focal-length wide-angle lens for photographing the ground markers, from which the attitude angles would be obtained in place of the conventional scales of a theodolite.

The primary error in determining the trajectory of the missile will be in the position determination of the airborne cinetheodolite, since the error between missile and cinetheodolite would only be two or three feet because of the shorter distance involved. The RC-7 test has indicated that the position of the cinetheodolite could be determined to approximately ±20 ft at 40,000-ft elevation, so the position of the missile as determined by two flying camera stations should be accurate to approximately ±30 ft. This means that the velocity data would be rather poor, as can be seen from the following computation:

A missile traveling at 2,000 fps, and having its position determined 10 times a second, travels 200 ft between frames. The velocity then equals:

$$V = \frac{d \pm \Delta d}{t}$$

or

$$\Delta V = \frac{\Delta d\sqrt{2}}{5t} = \Delta V = \frac{30\sqrt{2}}{1/10} = 420 \text{ fps error.}$$

This velocity error can be reduced by statistical methods of smoothing the curves to obtain useful data. For this reason, the principal use of the airborne cinetheodolite would be to determine aerodynamic characteristics such as pitch, yaw, roll, and path of trajectory.

Although air-launched missiles have been photographed from accompanying aircraft with tracking cameras, the design of a tracking sight that the pilot can use is a major problem. Tests made to date have involved an A3D airplane, which is roomy enough to accommodate a full-time camera operator. Because of the limited availability of such aircraft, a practical airborne cinetheodolite would need to be interchangeable with several single-place fighter-type jets.

Airborne Bowen Camera: Another variation of flying camera station would be to have a bank of fixed cameras which would function essentially as a set of Bowen cameras. These could be mounted in a wing-tip pod, with the position and attitude being determined by another camera photographing surveyed ground markers (Fig. 6). For tests where the desired trajectory coverage is limited and where a bank of cameras could be used, this would be a simpler operation and yet have approximately the same accuracy as the airborne cinetheodolite.

Conclusion

A flying camera station for missile coverage will be justified only at ranges beyond the useful limits of ground-based instrumentation. As the trend is toward smaller and faster missiles at higher altitudes, the demand is increasing for this type of instrumentation.

For aircraft orientation the flying camera station is very economical compared with a ground camera system and its associated range personnel and equipment. As the position accuracy is approximately the same, and attitude data are much better, the flying camera station is finding many uses in aircraft flight tests and instrument checks where attitude or position data are required.

Discussion

S. M. Lipton (Session Chairman): Would it be feasible to use tracking equipment with optical instruments in aircraft in an area which frequently has obscuring cloud conditions?

Mr. Kinder: That is actually what we are trying to prove: that we can track from an aircraft. Over clouds if you use gyros or some other artificial horizon, you can get your attitude information but you wouldn't get any trajectory data inasmuch as you would not have any position. The only basis for using a camera photographing the ground is to get position as well as altitude. But over clouds I think you'd probably use some other type or an artificial horizon.

Mr. Lipton: What is the maximum focal length you have been able to use on your lenses?

Mr. Kinder: The tests thus far are with a 16-in. lens on the camera; it's fixed and we just track with a mirror. We obtain fairly good results with that. We used it because it was convenient and available.

Optical Tracking Instrumentation

By A. H. SCHENDEL

The basic requirements for optical tracking instruments used in missile test work are outlined and a survey is given of the instrumentation presently in use and under development. Field operating conditions and data reduction aspects and *possibilities for future developments to meet the increasing demands for highly* accurate information on in-flight characteristics are discussed.

OPTICAL INSTRUMENTS have been used for determining the location of moving objects and for studying their behavior since Galileo, about 350 years ago, directed his telescope toward the sky.

In this age of aircraft, rockets and guided missiles, there is a continuous demand for improvement of methods and instrumentation to determine the trajectories of fast-moving objects, to ascertain their position in space, their velocity and acceleration, and to obtain information on attitude, roll and on external and internal events occurring during the flight. A variety of optical and electronic systems have been developed to meet these demands.

In the field of optical instrumentation it was sufficient, in former years, to make visual observations with telescopes. Increased speeds of airborne objects necessitated the development of photographic techniques to "freeze" the motion of the object in space so that a detailed analysis of the events can be made.

Two distinct optical-photographic methods are in use:

(1) The photographic camera remains in a fixed position (orientation). This method employs cameras which possess a wide angular field in order to cover a large portion of the trajectory, the object being recorded either on a photographic plate or on a strip of film. This type of instrumentation and its application on the missile range are discussed by J. E. Durrenberger.[1]

(2) The photographic camera continuously tracks the object. This method is described here. First, the essential features of an optical-photographic tracking instrument are considered.

Basic Requirements

To enable an optical tracking instrument to gather data on objects traveling at high velocities there must be:

(1) A long-focal-length telescopic system of high resolution to produce an image of the distant object of a quality and size adequate for obtaining the information wanted.

(2) A motion-picture camera to take photographs of the object at the required sampling rate, plus electronic equipment for synchronizing the camera and/or for recording time signals on the film to furnish a record of the events vs. time, and to enable correlation of the data with respect to other range instrumentation.

(3) A mount to carry the telescope and the camera, sighting telescopes and manual or power drives for smooth, vibration-free pointing of the camera at the target. In case the object is not readily visible, means have to be provided for acquiring the target, using information obtained from other instrumentation such as radar.

An instrument built to this specification will give a pictorial record of the external events vs. time from which information on attitude, roll, and other flight characteristics can be secured. To obtain position data, the instrument mount must be equipped with precision graduated circles and optical systems for photographic recording of the circles so that the azimuth and elevation angles under which the object was seen from the instrument site can be read from the film.

The determination of the coordinates (x, y, z) of a point in space by means of optical tracking instruments is based on a triangulation method requiring azimuth and elevation angle information from at least two instruments placed a suitable distance apart (base line). Obviously, a number of stations must be set up on the range to cover the trajectory of a missile. Because of the altitude and length of trajectories of modern missiles, an optical range instrumentation system is a fairly extended network of field stations requiring electrical power, wire lines or radio links, a time signal generator, control center, and competent personnel to accomplish the operation.

Tracking Instruments, Operating or Under Development

Cinetheodolites: An instrument widely used on missile ranges for trajectory determination is the Askania cinetheodolite (Fig. 1), developed by Askania Werke, Berlin, Germany. As the name implies, this instrument combines the features of a theodolite as used in geodetic work with those of a motion-picture camera. The camera provides for frame rates up to 5/sec. The individual frames are triggered by pulses transmitted from range timing. Interchangeable lenses of a focal length from 60 to 300 cm with relative apertures from *f*/4.5 to *f*/15 are employed. Tracking of the instrument in azimuth and elevation is usually accomplished by two operators using handwheels. One-man operation or remote control can also be provided. On each frame (Fig. 2), simultaneously with the image of the test object, a record is obtained of the azimuth and elevation

---

Presented on May 2, 1957, at the Society's Convention at Washington, D.C., by A. H. Schendel, Range Instrumentation Development Div., Integrated Range Mission, White Sands Proving Ground, N.M.
(This paper was received on November 8, 1957.)