NATIONAL BUREAU OF STANDARDS REPORT

10 896

INSTRUMENTATION FOR OPTICAL MEASUREMENT
OF
BUILDING DEFLECTIONS

NBS

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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INSTRUMENTATION FOR OPTICAL MEASUREMENT OF BUILDING DEFLECTIONS

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Center for Building Technology
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CONTENTS

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ABSTRACT

An optical system is proposed for measuring the horizontal deflection of a building in response to lateral forces. The system overcomes some of the difficulties of monitoring such deflections continuously. It can measure both short-term and long-term deflections. Instrumentation consists of two parts: a target light mounted at the deflecting point, and a tracking telescope mounted at a fixed datum. Problems are common with other systems using long optical paths; air temperature gradients in the light path contribute the largest errors. In initial experiments, an angular resolution of 10^{-5} radian (0.01 inch at 100 feet) has been achieved with a bandwidth of 50 Hz, and better resolution is possible.

THE MEASUREMENT PROBLEM

The effects of wind loads, temperature changes, and seismic forces are important in the design of tall buildings. Building deflection is of particular interest, and characteristics that influence the deflection are (1) the effective stiffness, (2) the natural frequency, (3) the damping, and (4) temperature-induced deformations. The usually important deflection frequencies extend to 10 hertz (Hz), and a deflection resolution of 0.01 inch is a useful measurement goal.

Most deflection measurements so far have been made with inertial instruments having natural frequencies somewhat below 0.1 Hz. However, inertial instruments can be affected by unwanted motions such as rotation, and they are impractical for measurements much below 0.1 Hz in frequency. Low-frequency measurements must be made with an instrument fixed in relation to a reference datum.

OPTICAL METHODS

Optical measurements of building deflection have been made using two general schemes, longitudinal (path-length) sensing and transverse (path-angle) sensing. Longitudinal measurements use pulsed radiation as in the geodimeter and radar. They require an air path outside of the building with a suitable fixed location for the instruments. Achievable resolution is of the order of 0.04 inch. Transverse visual measurements using theodolites or transits require the same facilities.

If a vertical shaft is available, a transverse measurement can be made conveniently inside the building. Long-term deflections can be measured if the instrumentation has the necessary electrical and mechanical stability. The system using a target and tracking telescope at opposite ends of a vertical path is potentially capable of monitoring displacements of 0.01 inch. Variants of such a system include interchanging target light and telescope, using a laser or tungsten light source, using a null-seeking position sensor or proportional-output sensor, a servo-controlled target or servo-controlled deflecting mirrors in the optical path, and so on. All of these arrangements are capable of the same accuracy when developed, but practical considerations narrow the choices. First, a laser is not permitted in many suitations because of the possibility of eye injury. Second, a non-directional target light or telescope is required at the deflecting point for the system to be insensitive to rotation or tilt. Third, mechanical servos of sufficient displacement have relatively slow responses; for this application, proportional-output sensors seem more practical.

THE EXPERIMENTAL INSTRUMENT

The instrument assembled for experiment is shown schematically in Fig. 1. The target, a tungsten lamp with collimating lens, is fixed to the deflecting point P. The tracking telescope, with its semiconductor light sensor, is fixed to the reference datum G. The sensor is a silicon photovoltaic cell having four output terminals disposed about its 0.4-inch square surface. The terminals are used in perpendicular pairs. A light spot projected on the surface generates a pair of currents that are functions of spot position and can be used to measure the target displacement, as will be shown.

The target, also shown in Fig. 1, uses a 6-volt, 9-ampere ribbon-filament lamp, mounted vertically to meet the requirement for base-down operation. To direct the beam downward, a mirror at 45 degrees is placed between the lamp and collimating lens, which has a focal length of 3 inches and a diameter of one inch. The lens is placed so that the filament image projects to a focus at a distance of about 200 feet, the approximate range for the measurement. For very long ranges, a larger collimating lens might be needed to produce sufficient light flux at the telescope.

The tracking telescope Fig. 2, uses an objective lens 3 inches in diameter with a focal length of 19.5 inches. The objective is followed by a negative lens consisting of two 4-diopter meniscus lenses having an effective focal length of minus 5 inches. Sliding the negative lens along the axis changes the focus, which is not critical because of the averaging characteristic of the sensor. To conserve space and improve rigidity, the optical path is folded into a box by using two fixed mirrors.

A real image is focussed on the sensor which is tilted a few degrees from perpendicularity with the axis so that light reflected from its surface is directed away from mechanical parts, thereby avoiding re-flections that might affect the sensor response. The sensor can be rotated in its mount to align the sensor's axes with the axes of the box. A square of flat, parallel glass 0.04 inch thick is mounted in the optical path near the sensor. The plate can be tilted by a motor driven through an angle that is set by adjustment of mechanical stops. Tilting the plate displaces the image at the sensor by a distance equivalent to an angular change of the target. The equivalent target displacement can then be calculated for a known range.

A separate lens mounted on the side of the box is used as a finder for coarse initial adjustment. The target image projects on a screen with crossed lines to indicate the alignment axes. Large errors are easily seen and corrected. The box dimensions are approximately 4 by 10 by 16 inches, and the material is 1/4-inch aluminum plate. A three-point adjustable mount uses adjustment screws spaced 16 inches apart resting on metal pads to provide stable contact areas for the screws.

ELECTRONIC DETAILS

We define the displacement sensitivity of the instrument as the output voltage resulting from a target displacement, in either the X or Y direction, divided by the displacement. Thus, if E_x is the X-axis output voltage, and X is the corresponding displacement of the target, then the displacement sensitivity is $S_x = E_x/X$. Similarly, $S_y = E_y/Y$.

The schematic diagram of the electronic circuits is shown in Fig. 8. The four output currents of the light sensor are amplified in differential pairs corresponding to the X and Y axes. The amplified differential currents are converted to voltages E_1 and E_2, respectively, by amplifiers 1 and 2. The sum of the four sensor currents is converted to a voltage E_3 by amplifier 5. E_3 is proportional to the light intensity, while E_1 and E_2 are each proportional to both the light intensity and to their respective deflections. The ratio $(1/E_3)(E_1/X)$ will then be equal to $S_x = E_x/X$ except for a multiplying constant.

Modifying E_1 and E_2 with the inverse of E_3 is accomplished with a dual inverse multiplier circuit, the control being based on variable duty-cycle gating. A free-running rectangular-pulse oscillator with controllable duty cylce is formed of transistors Q_1 and Q_2. Q_3 and Q_4 comprise the control, the control point being the base of Q_4. Field-effect transistors G_1, G_2, and G_3 are analog gates controlled by the oscillator and driver Q_5. The gated signals appear at followers A_3 and A_4 which supply current at low impedance to the output terminals to drive recorders or other external devices.

EXPERIMENTAL PERFORMANCE

Pilot tests were made under operating conditions in an elevator shaft with a 160-foot range. The elevators were in use most of the time. Because of limited space, the optical path was within eight inches of one wall, and it was expected that the effects of air temperature gradients from various heat sources would be seen in the records. There were noticeable instabilities, and they were especially noticeable when the elevators were not in use, probably because of convection columns in the undisturbed air. When the air was mixed, the effects were smaller.

Recordings as long as several weeks showed building deflections due to winds and a diurnal deflection due to solar heating. The deflections were in the range of a few hundredths of an inch as the 160-foot range, the records being readable to about one hundredth of an inch, which was the noise level for this experiment. Laboratory tests of the instrument under fixed conditions with no air path reveal no detectable drift in the electronics. The telescope itself deforms slightly in response to temperature changes, however, so that it must be installed carefully to protect it from large temperature variations.

To test the instrument for deflection sensitivity and accuracy of axis alinement, a horizontal test range was established in a temperature controlled room with a path length of 100 feet as shown in Fig. 5. Fig. 6 shows a target mounted so that motion can be made in each axis. Fig. 7 shows the telescope mounted horizontally and also some of the test equipment. Fig. 4 shows the instrument and electronics case in a vertical test stand used in the development.

Additional tests of the instrument are being made in a controlled environment and in typical conditions in a high-rise structure.

OPTIMUM DESIGN AND PERFORMANCE

The optical resolution of a system such as the one described here depends on several factors that affect the image of the target at the telescope sensor. The geometry of the sensor in the image plane of the objective lens is shown in Fig. 3, where S is a side of the square sensor area, D is the image diameter (influenced by the focal length and spreading due to diffraction and focus errors), and $x_{max} = S-D$ is the limit of linearity of the system. The resolution in the image plane is related to the dimension S and is determined by the light flux and the stability of the sensor and electronics. It is found experimentally.

Several compromises must be made in order to set optimum values for the focal length of the objective lens and the diameter of the target. A large target diameter increases the total light flux but also increases the image diameter at the sensor, reducing the displacement limit. A target diameter approximately one-tenth the expected maximum displacement appears to be a reasonable choice, as linear operation can then be obtained over most of the detector area. The required focal length is then the range multiplied by nine-tenths the sensor width and divided by the maximum expected target displacement.

In practice, the displacement resolution seems to be limited neither by the optics nor by the mechanical stability of the instrumentation or electronic noise, but by non-uniformity in the refractive index of the optical path. A temperature variation of the air in the direction of the path would be undetectable, but variations perpendicular to the path change the direction of the light rays and thereby the apparent position of the target. For a range of 100 feet and a uniform transverse gradient of one Celsius degree per inch, the apparent displacement is one inch. These are quite artificial assumptions, however, and a uniform gradient almost never is maintained over such large ranges.

If the path were divided into smaller regions having gradients of random magnitudes and directions, a light ray will be bent varyingly along its length and will arrive deflected in the nature of a random walk. Since bending is an angular change, the apparent displacement of the target is least when the bending occurs near the target and greatest when near the telescope. A relatively stable path can be established if the air is thoroughly mixed or given a moderate velocity to create turbulence and reduce the magnitudes of the temperature gradients.

ACKNOWLEDGEMENT

This report, which is primarily an engineering description of specific instrumentation, includes also a certain amount of background material covering the overall measurement application. The author wishes to acknowledge the suggestions and contributions of the staff of the Building Research Division, particularly of Dr. Robert Crist, Structures Section, in the preparation of the background material.

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3. Morecos, J., Castanheta, M., and Trigo, J. T., Observation of Tagus River Bridge in Lisbon, Ministerio Das Obras Publicas, Laboratorio National de Engenhama Civil, LNEC-Proc 37/1/2203 (Lisbon Portugal, March 1968).

LIST OF FIGURES

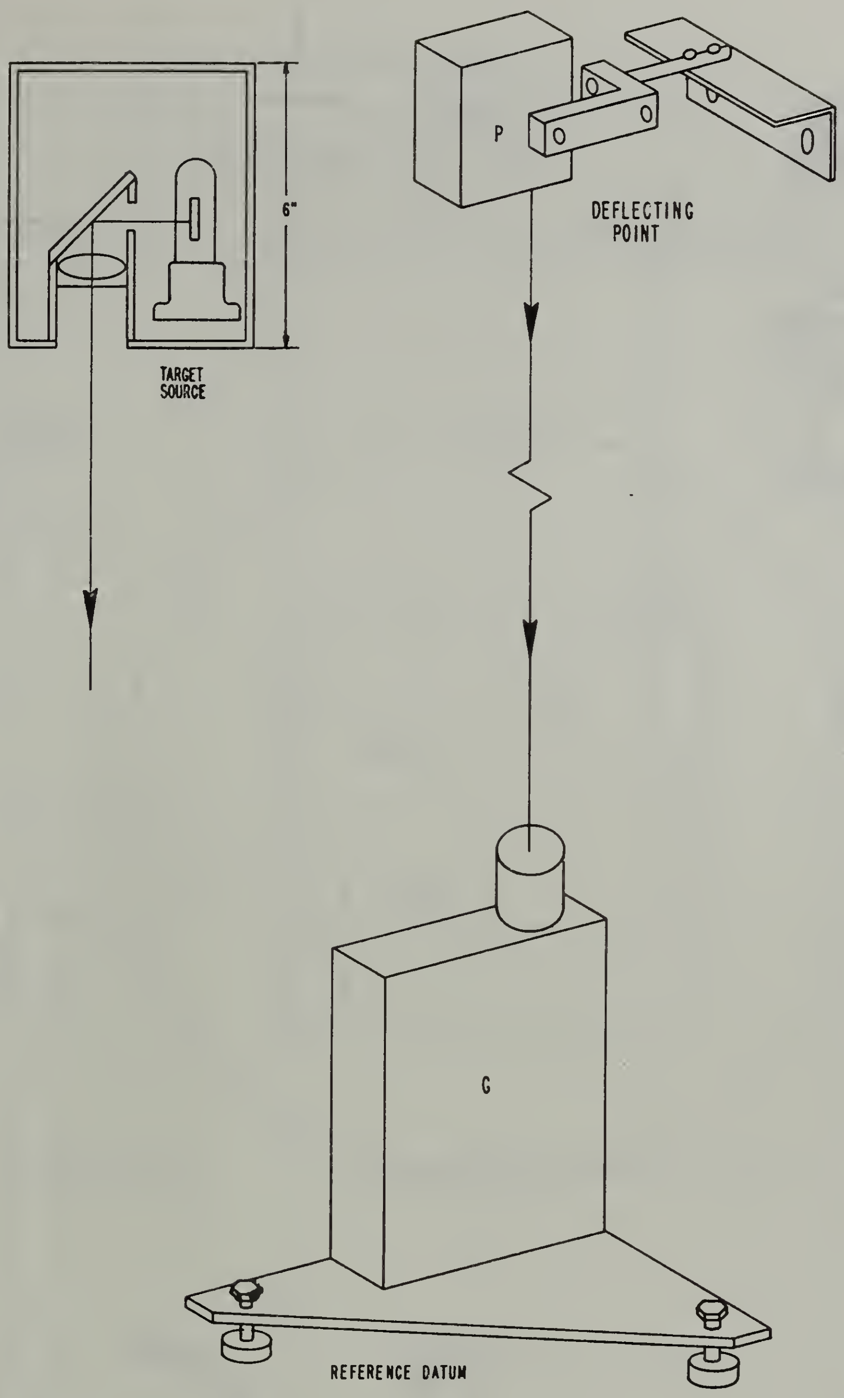

FIG. 1 SYSTEM LAYOUT

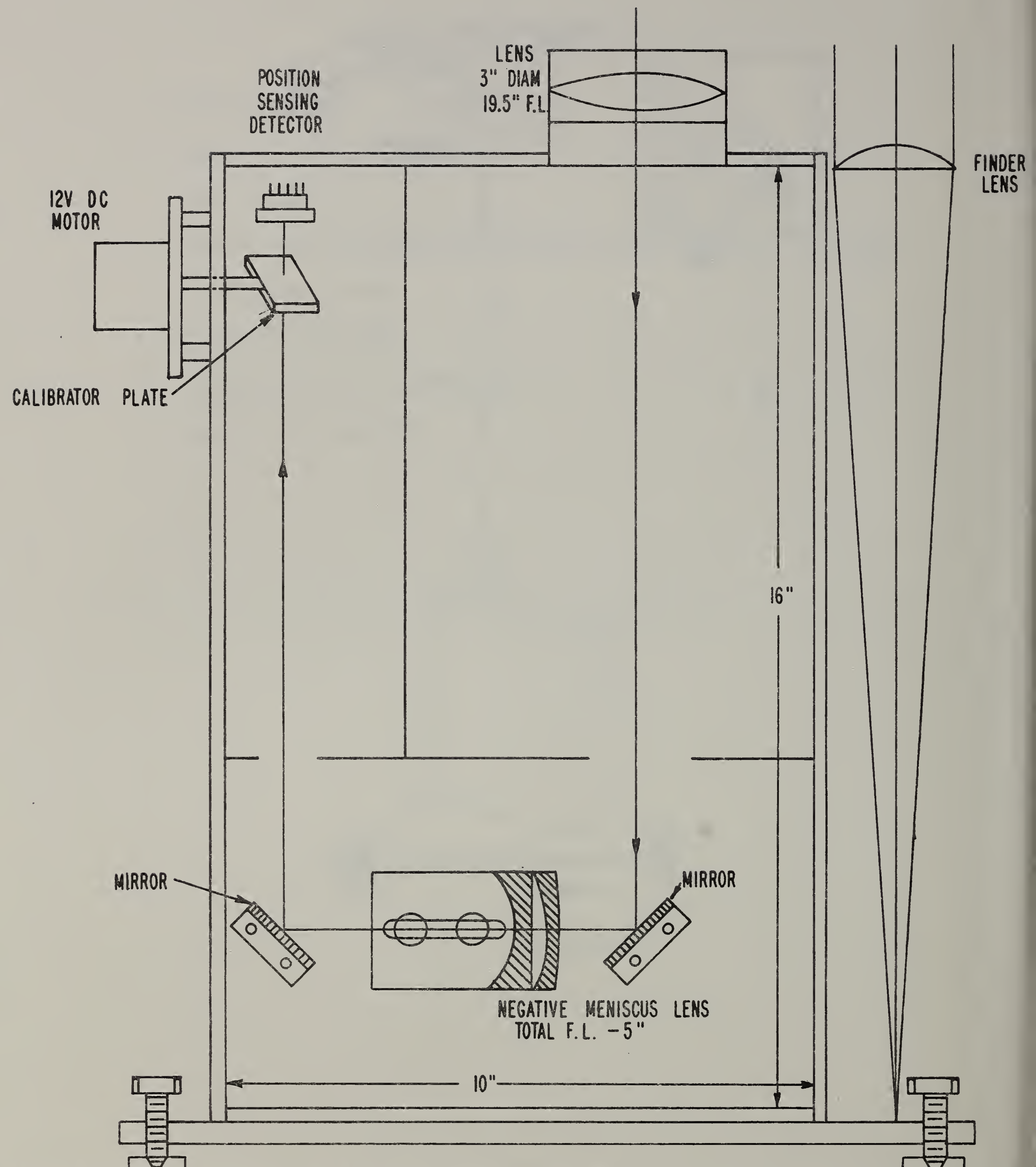

FIG. 2 LAYOUT OF TRACKING TELESCOPE

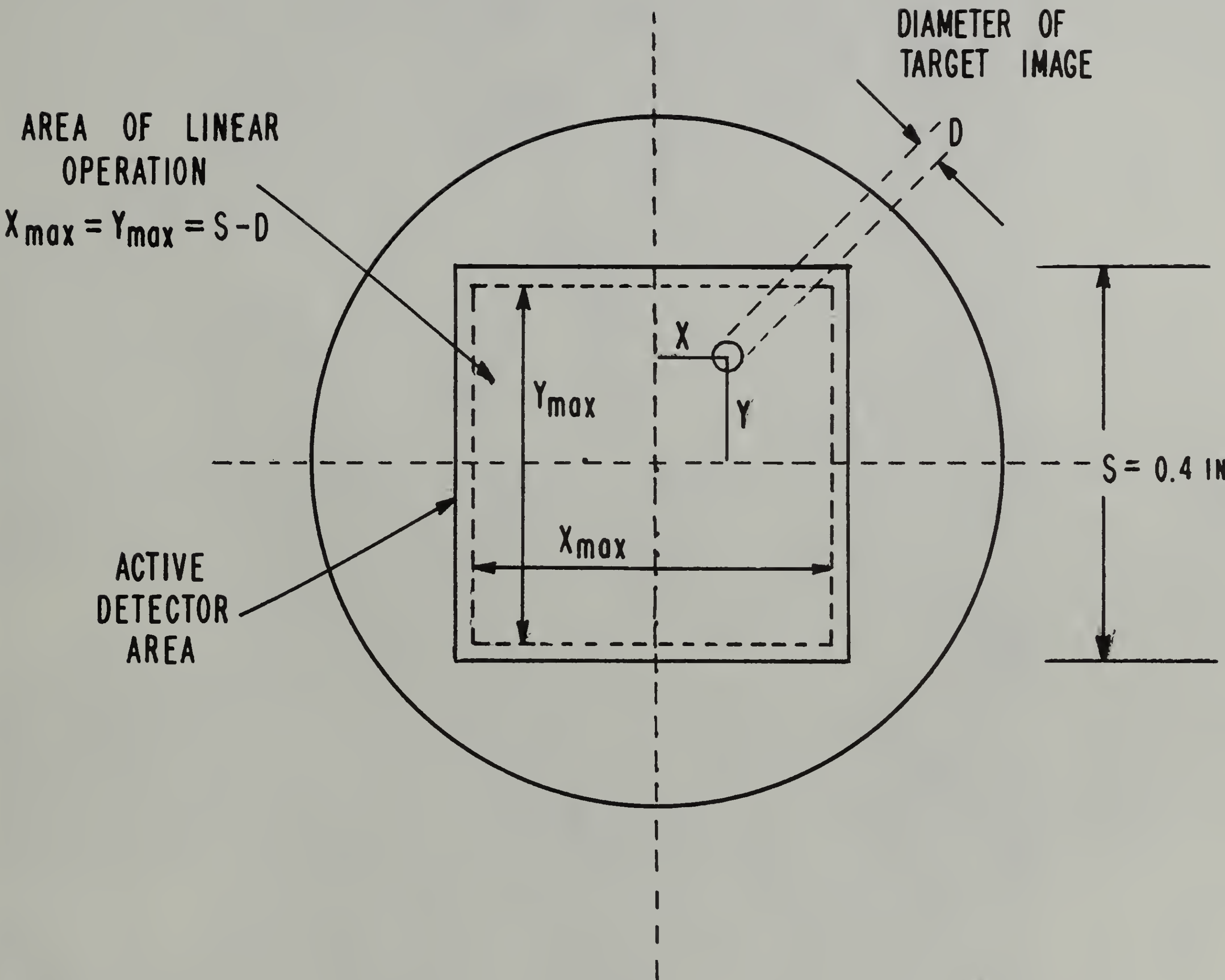

FIG. 3 SENSOR GEOMETRY

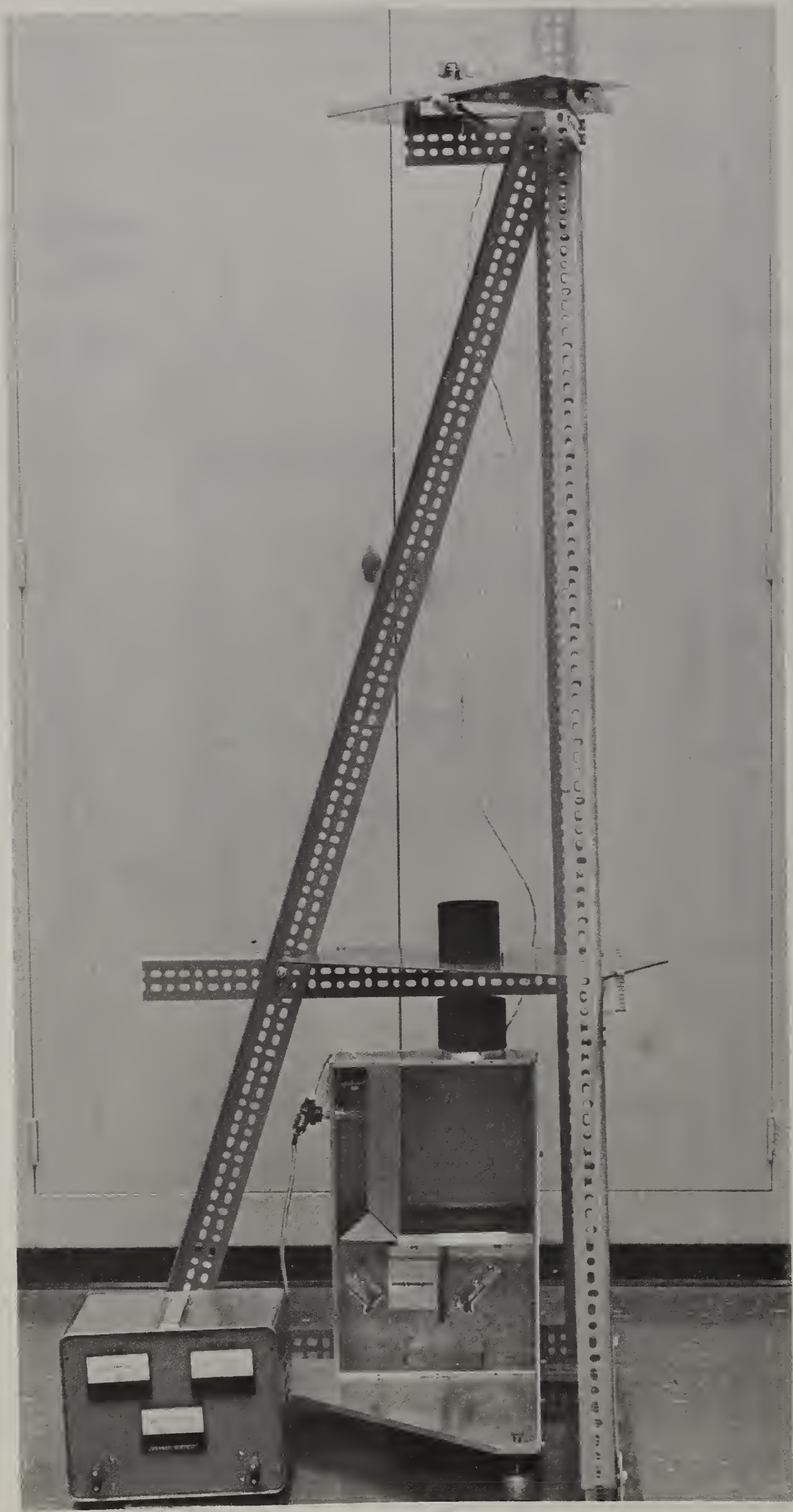

FIGURE 4 VIEW OF INSTRUMENT AND ELECTRONICS IN DEVELOPMENTAL TEST STAND

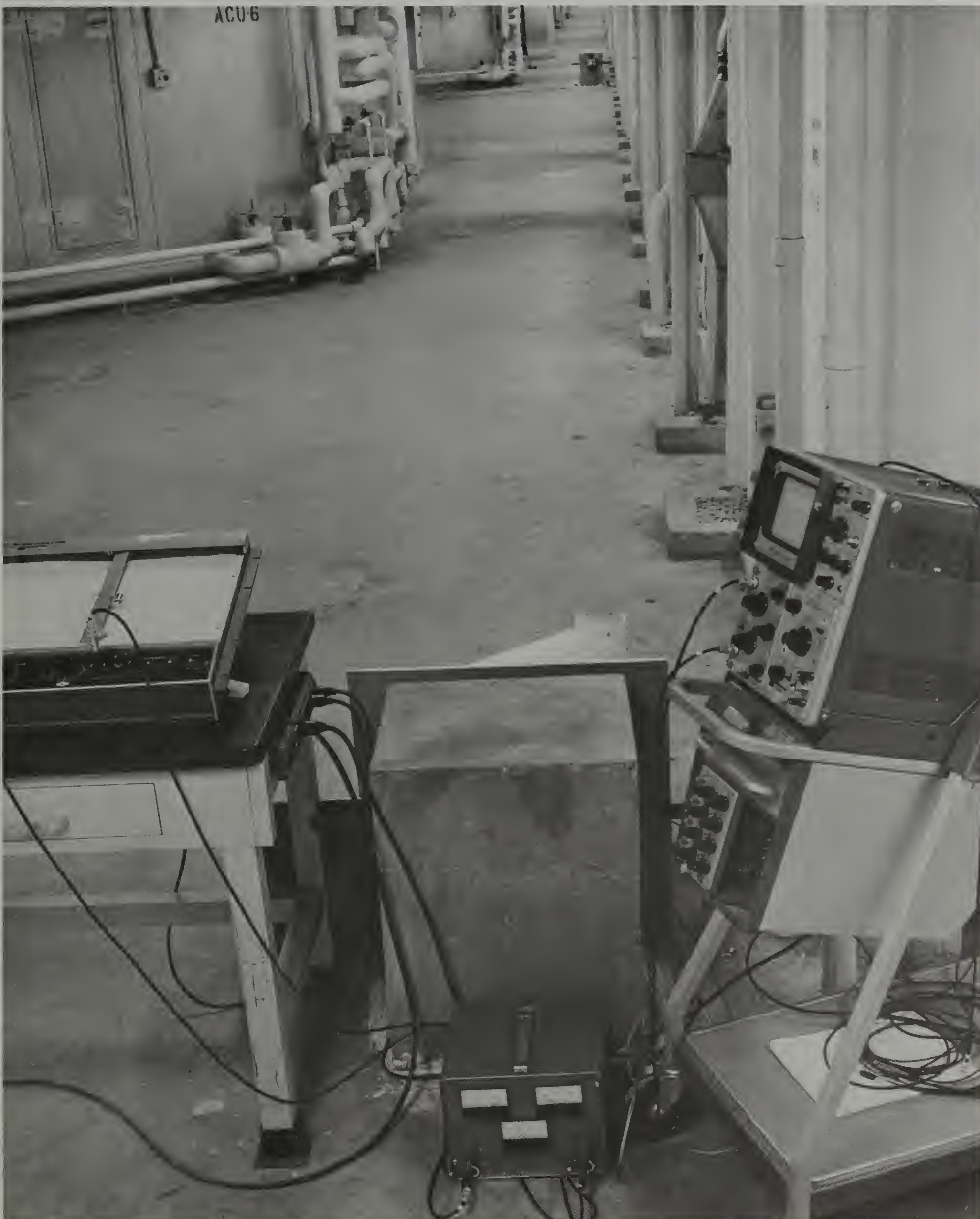

FIGURE 5 100-FOOT TEST RANGE

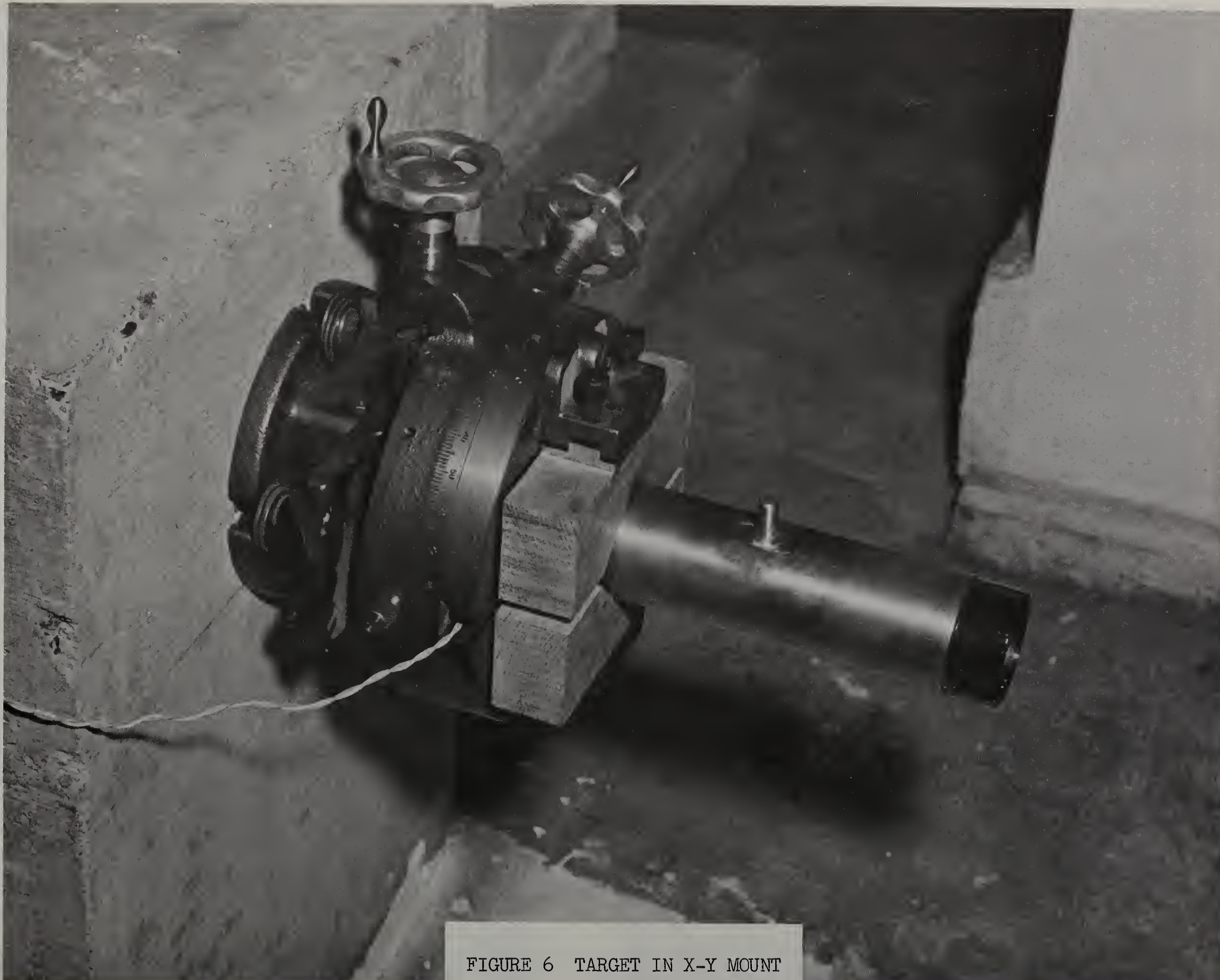

FIGURE 6 TARGET IN X-Y MOUNT

FIGURE 7 TELESCOPE AND TEST EQUIPMENT

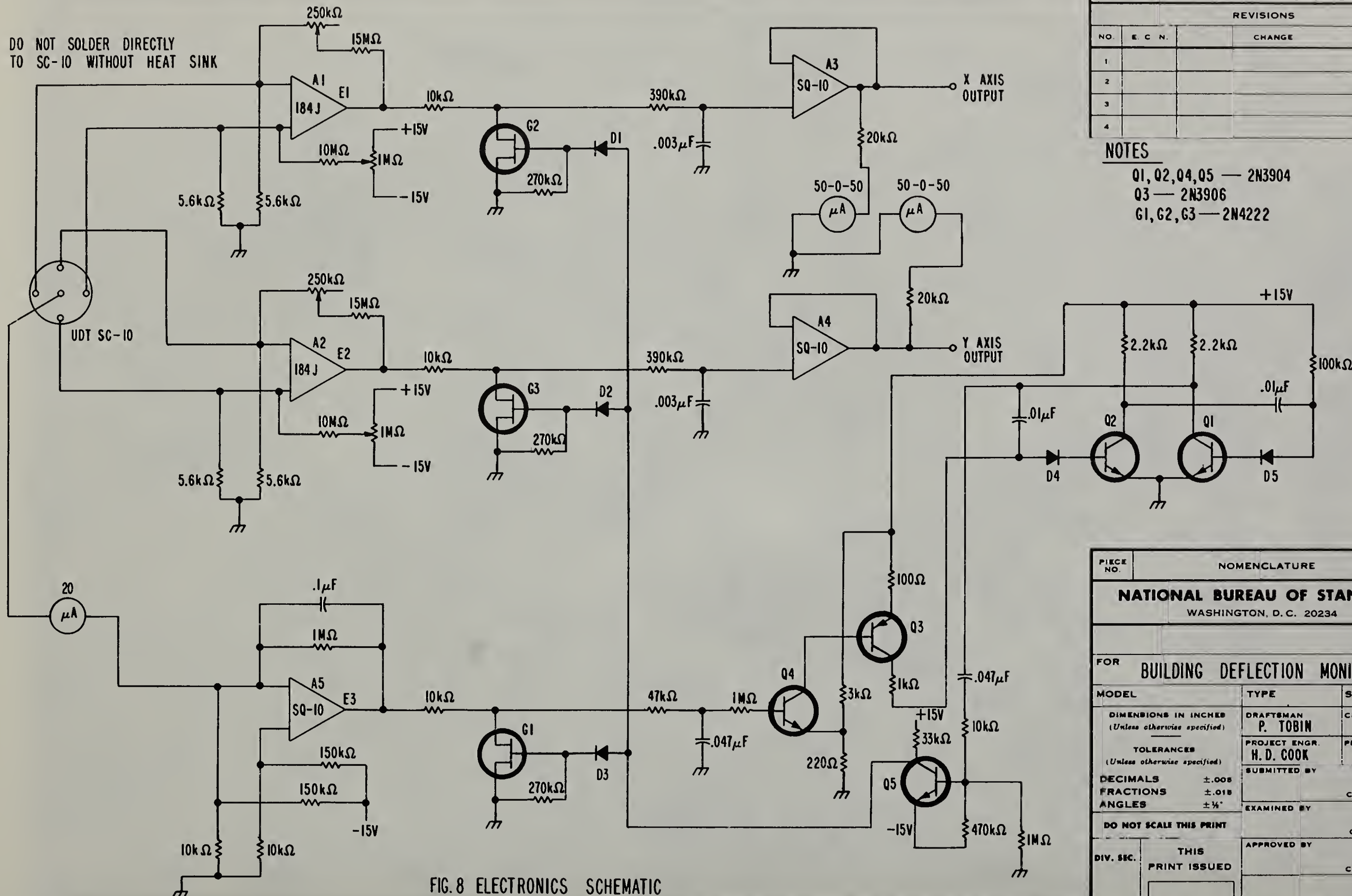

FIG. 8 ELECTRONICS SCHEMATIC

ORIGINAL DATE OF DRAWING 2-8-72

REVISIONS

NO.	E. C. N.	CHANGE	DATE
1			
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4			

NOTES

Q1, Q2, Q4, Q5 — 2N3904
Q3 — 2N3906
G1, G2, G3 — 2N4222

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