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AN ANTENNA MEASURING INSTRUMENT AND ITS USE ON THE 140-FOOT TELESCOPE

J. W. Findlay and John M. Payne

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1.0 Introduction

This paper is an up-to-date version of the original report on the instrument written by J. Payne (1). The description of much of the circuitry of the instrument is not repeated here. A more extensive set of ground tests has been made and a new set of measurements on the 140-foot telescope is described.

A C.W. radar technique is used to measure distances from near the focal point of the reflector to various points on the reflector surface. The system described is able to measure changes in distance from the focal point to 21 points on the surface simultaneously with a short-term accuracy of 0.002" (0.05 mm). The long-term stability of the instrument is affected by changes in the atmospheric refractive index. Compensation for these changes is possible and is routine on distance measuring equipment using a modulated light beam. No attempts at compensation have been made in the present equipment.

By using frequency switching techniques it would be possible to modify the instrument to measure absolute distance rather than changes in distance.

The principle of this type of measurement has been known for some time (2). Swarup and Yang (3) used it for the phase adjustment of large arrays; their paper gives other references.

The instrument has been installed on the 140-foot telescope and measurements made from near the focal point to four points on the surface.

2.0 Principle of Operation

2.1 General Description

Figure 1 shows the components of the measuring system.

A stable oscillator at X-band (11.8 GHz) transmits a signal via a circulator and a broad beam horn antenna. A transponder is situated at the other end of the path over which the distance has to be measured. This transponder receives the carrier frequency, amplitude modulates it at a frequency of 455 kHz and retransmits it. The receiver is sensitive only to the transponded signal and rejects signals at the carrier frequency.

The output of the receiver is a signal at 455 kHz. The phase of this signal, referred to the modulating signal provided to the transponder, is a measure of the phase difference between transmitted and received signals at the carrier frequency. The wavelength of the carrier frequency is 1 inch, so a phase change of 1° corresponds to a change in the path length of about 0.0027" (0.07 mm).

2.2 Theory of the System

To avoid the introduction of many constants the magnitude of the various signals will be ignored and phase relationships only will be considered.

The output from the transmitter is given by cos $\omega_0 t$ where ω_0 is carrier frequency (in radians/sec).

The signal received at the transponder is $\cos(\omega_0 t + \phi_1)$, where ϕ_1 is the phase shift at the carrier frequency and is given by

$$\phi_1 = \frac{2\pi d}{\lambda_0}$$

where d is the distance from the transmitter and λ_0 is the wavelength of the carrier frequency.

The transponder retransmits this signal as $\cos \omega_m t \cos(\omega_0 t + \phi_1)$, where ω_m is the modulating frequency.

This may be rewritten as

$$\cos\left[\omega_L t + \phi_1\right] + \cos\left[\omega_u t + \phi_1\right]$$

where

$$\omega_u = \omega_0 + \omega_m \text{ (the upper sideband)}$$

$$\omega_L = \omega_0 - \omega_m \text{ (the lower sideband)}$$

The retransmitted signal will be phase shifted again on its return to the receiver. The signal received will be

$$\cos\left[\omega_L t + \phi_1 + \frac{2\pi d}{\lambda_L}\right] + \cos\left[\omega_u t + \phi_1 + \frac{2\pi d}{\lambda_u}\right]$$

where

λ_u = wavelength of upper sideband

λ_L = wavelength of lower sideband.

The inputs to the two mixers (assuming equal path lengths in the receiver) will be given by

$$\cos\left[\omega_L t + \phi_1 + \phi_2 + \frac{2\pi d}{\lambda_L}\right] + \cos\left[\omega_u t + \phi_1 + \phi_2 + \frac{2\pi d}{\lambda_u}\right]$$

where ϕ_2 is the additional path length added in the microwave circuit of the receiver.

This may be rewritten as

$$\cos\left[\omega_L t + \Phi_1\right] + \cos\left[\omega_u t + \Phi_2\right] \tag{1}$$

where $\Phi_1 = \phi_1 + \phi_2 + \frac{2\pi d}{\lambda_L}$

and $\Phi_2 = \phi_1 + \phi_2 + \frac{2\pi d}{\lambda_u}$.

The output from mixer A will be the input multiplied by $\cos \omega_0 t$. This output signal enters the IF amplifier following the mixer. Since this amplifier only passes frequencies near ω_m, its output can be shown (after some algebra) to be:

$$\cos\left[\omega_m t - \Phi_1\right] + \cos\left[\omega_m t + \Phi_2\right] \tag{2}$$

The output from mixer B will be the input (equation 1) multiplied by $\cos\left[\omega_0 t - \frac{\pi}{2}\right]$; this gives, after the signal has traversed the IF amplifier:

$$\cos\left[\omega_m t - \Phi_1 - \frac{\pi}{2}\right] + \cos\left[\omega_m t + \Phi_2 + \frac{\pi}{2}\right]$$

This signal from mixer B is phase shifted $-\frac{\pi}{2}$ at the modulating frequency giving at the point of addition:

$$\cos\left[\omega_m t - \Phi_1 - \pi\right] + \cos\left[\omega_m t + \Phi_2\right] \tag{3}$$

The outputs of the two IF amplifiers are made equal and then added. When equation (2) and equation (3) are added, the first two terms cancel and a term remains that is proportional to $\cos\left[\omega_m t + \Phi_2\right]$.

This signal, after passing through a limiting amplifier, is phase detected using ω_m as a reference. This phase detector is linear and has a range of 360°. The output will be proportional to Φ_2 which is equal to

$$\phi_1 + \phi_2 + \frac{2\pi d}{\lambda_u}$$

but $\phi_1 = \frac{2\pi d}{\lambda_0}$, ϕ_2 is a constant, and $\frac{1}{\lambda_u} = \frac{1}{\lambda_0} + \frac{1}{\lambda_m}$. The output of the phase detector is then

$$\frac{4\pi d}{\lambda_0} + \frac{2\pi d}{\lambda_m}$$

$\lambda_m >> \lambda_0$, so the output is proportional to $\frac{d}{\lambda_0}$ and thus is a measure of the length of the path in terms of the RF wavelength in air.

3.0 Analysis of the System

3.1 Signal Strength Analysis

The oscillator used was a Gunn diode with a power output of 100 mW at 11.802 GHz (λ_0 = 1.000").

The design of the transmitter/receiver horn antenna was quite difficult. The angle subtended by the 140-foot reflector at the focal point is 121° and, unlike the normal feed horn, we would like high illumination at the edges. Open-ended waveguide at this frequency gives a half-power beamwidth of about 70° in the H-plane and 120° in the E-plane. The horn as finally designed is shown in Figure 2. By sliding the plate behind the horn, we were able to obtain a half-power beamwidth of 110° in the H-plane and 140° in the E-plane.

A suitable horn for the transponder is a 23 dB horn with dimensions as shown in Figure 3. This horn has a beamwidth of 18°, so that alignment of the transponders on the telescope would not be difficult.

The receiver noise figure was 15 dB and the bandwidth after the phase detector was 100 Hz. After making allowances for various losses, the calculated signal-to-noise power at the phase detector was 46 dB, when the measurement distance was 70 feet (21.4 m) with the components already described. This noise shows at the output of the limiting amplifier as phase jitter. The rms value of this may be calculated by considering the noise voltage to be added vectorially to the signal voltage. In this case the noise voltage is $\frac{1}{200}$ of the signal voltage, so the rms value of the phase jitter will be $\frac{1}{200}$ radians or 0.29°. This suggests that the jitter in the measured path length due to receiver noise would be about 4×10^{-4} inches (0.01 mm), an entirely acceptable value.

3.2 The Phase Shifts and Signal Balance

The two phase shifts of 90° and the final equilization of the signals from mixer channels A and B before addition are critical to the performance of the system. Adjustment of the 90° phase shift at the IF was straightforward. The 90° phase difference between the LO signals applied to mixers A and B was realized by the adjustment of line stretchers in the LO lines. This adjustment was made most easily when the instrument was under test on the ground range (see paragraph 5). When this phase shift is correct the ranges at which minimum signals at the outputs of mixers A and B occur will differ by exactly $\frac{\lambda}{8}$. With the instrument mounted on its precision slide carriage, this fact was used to adjust the LO phase difference. The amplitude balance adjustment was straightforward.

The final test that these phase and amplitude adjustments were correct was two-fold. As the range (in the ground tests) was changed over $\frac{\lambda}{2}$, the summed signal amplitude at the phase detector input should not change. Also, over a similar range change, the plot of recorded range versus actual range should be linear. Wrong adjustments result in changes in the signal amplitude and range non-linearity. As Figure 6 shows, the instrument was correctly adjusted in the ground tests.

3.3 Stability Analysis

The stability of the instrument over the duration of an experiment is mainly determined by

(1) The stability of the Gunn diode oscillator;

(2) Phase changes in the coaxial cable sending the modulating signal to the transponders;

(3) Changes in atmospheric refractive index.

The main effect on oscillator stability is that of changes in diode temperature. (The diode frequency also depends on the voltage supplied, but this can be well-stabilized.) The frequency stability required to hold variations of a measured distance of 20 meters (66 feet) to 0.025 mm (0.001 inch) is 1.3 in 10^6. This stability can be achieved with a well-designed Gunn diode, although some diodes were found to drift in frequency by considerably greater amounts as their temperature changed.

The cables to the transponders were about 100 meters of RG 58-U. It can easily be shown that temperature changes of 20° C are needed if phase changes in these cables are to give distance errors of 0.025 mm (0.001 inch).

Since distances are measured in terms of the radio frequency wavelength in air, the refractive index of air affects the measurements. For radio wavelengths, the variations in water vapor content are most important, as the following example shows. Over a measured distance of 20 meters (66 feet) in a normal atmosphere:

— A 1° C increase in air temperature decreases the measured range by 0.02 mm (0.008 inches).

— A 10 millibar increase in atmospheric pressure increases the range by 0.05 mm (0.002 inches).

— A 1 millibar increase in water vapor pressure increases the range by 0.08 mm (0.003 inches).

In paragraph 5 we give examples of the distance changes observed during the ground tests.

4.0 General Description and Operating Procedures

The block diagram of the system is shown in Figure 1. The transmitter/receiver was built in a temperature-controlled box. About 100 meters of RG 58-U cable connected each transponder to the control and display unit. For the ground tests the transmitter/receiver box was mounted on a precise optical bench so that its movements could be measured. For the telescope tests it was rigidly mounted near but not at the focal point of the telescope. The control and display unit was near the T/R box in the ground tests and in the control room for the telescope tests.

A photograph of the control and display unit is shown in Figure 4. Each transponder is identified by an indicator lamp which has associated with it a thumbwheel switch (giving 45° phase steps) and a ten-turn potentiometer (for fine phase control). A digital display reads displacements in increments of 0.001". The control unit can handle up to 21 transponders; only four were used in the present tests.

Two operating modes are possible. In the manual mode any one transponder may be selected and distance changes monitored on the digital meter. Normally, this mode is used for initial set up of each transponder output at the start of a measuring period.

The automatic mode involves switching a transponder on for a period of 18 ms, measuring the distance and storing the result in a sample-hold circuit. The next transponder is then switched on and the procedure repeated. This scanning technique gives 21 voltage outputs that represent the 21 distance changes. These voltages are available continuously and are updated every 0.44 sec.

A typical set up procedure involves setting the output from each channel to be near zero with the telescope set at zenith. This is done by using the manual mode and setting the distance output close to zero for each transponder by using the fine and 45° phase controls. The 45° phase control is a thumbwheel switch giving precise 45° steps in phase to the modulating signal provided to the transponder. This corresponds to a distance change of 0.0625" (1.59 mm). The final meter setting is done with the fine phase control potentiometer. The instrument may then be switched to the automatic mode and up to 21 outputs continuously recorded as the telescope is moved. In observing on the 140-foot telescope some of the distance changes were as large as 9 mm (0.36 inches). It was found to be easier to avoid the "phase-jump" parts of the phase detector output (which occur every 0.5 inch of range) by switching in or out the 45° phase steps and then adjusting the final data for these steps.

5.0 Ground Tests of the System

The instrument and four transponders were set up on a stable ground-range as shown in Figure 5. The height of the instruments was about 1.5 m (5 feet) above grass-covered ground. The instrument could be moved over a few inches on a sliding carriage along the line towards transponder number 2, and its position could be recorded to ± 0.03 mm ($\sim 10^{-3}$ inch).

5.1 Accuracy and Linearity

We took care to adjust the instrument, particularly in setting the two 90° phase shifts required for its correct operation, and made a number of calibrations by moving the T/R box in steps of 0.05 inches (1.27 mm) and recording the readings. A typical result on a day where atmospheric affects were small is shown in Figure 6. The rms departure of a single point from the line is 0.075 mm (0.003 inch). The slope of the line is close to unity; we did not attempt to set this slope value exactly, since in use the instrument is calibrated by using the accurately known 45° phase shifts. The break in the line occurs at the phase change-over (where the total path length change goes through one RF wavelength—nominally 2.54 cm). Observations close to this region are unreliable, and it was such observations which invalidate some parts of the 1970 measurements on the 140-foot telescope.

5.2 Atmospheric Effects

The ray paths used in these tests were parallel to the ground and thus the small changes in refractive index of the air near the ground showed well in the observations. On occasion, the fluctuations over a 20 m distance were as large as 1 mm (0.04 inch). The record for a fairly good day was analyzed over 40 minutes and showed an rms (1 σ) flcutuation of 0.1 mm (0.004 inch). Some night-time results showed lower fluctuations.

The telescope observations, taken between 1000 and 1400 hours EDT on September 11, showed no detectable atmospheric effects down to the ± 0.1 mm (0.004 inch) level. The fluctuations observed during the ground observations seem to be reasonably consistent with those stated in paragraph 3.3, but no actual measurements of the atmosphere were made during the ground tests.

6.0 Tests on the 140-Foot Telescope

Four transponders were mounted on the surface of the 140-foot telescope, each at a radial distance of 15.9 meters (52 feet) from the reflector center. When the telescope was pointed to the zenith the transponders were N, S, E and W, respectively, and they are identified in this way in what follows. The T/R box was bolted to the west side of the "donut" and the feed was about 40 inches (1.0 m) to the west of the focal point of the telescope.

Measurements were made between 1000 and 1400 hours EDT on September 11, 1973; typical results for movements in declination (at a fixed hour angle of zero) are shown in Figure 7. Figure 8 shows results of moving the telescope over +6 hours to -6 hours at a declination of +38° 26'. Some results were repeated, and a roll from -5 hours to +5 hours at $\delta = 0°$ was also made.

The general reproducibility of results was good. The north and south transponders giving the results in Figure 8 show deflections which repeat to a (1σ) error of 0.145 mm (0.006 inch). However, the east and west transponders show a possible hysteresis effect; the corresponding (1σ) error for them is 0.30 mm (0.012 inch). Whether this effect is due to the structure or to the surface panels cannot yet be decided.

7.0 Comparison with Computed Deflections and Conclusions

Woon-Yin Wong has made an extensive set of computations of the deflections of those parts of the 140-foot telescope above the declination axis. He will describe these in a separate report, but he has derived from his results the expected changes in the lengths which we have measured. We are grateful for his permission to show these results as the dotted curves on Figures 7 and 8.

The computations include the effects of the bending of the main reflector support structure, of the feed legs and of the resulting displacements due to our mounting of the T/R box at a point away from the axis of symmetry. Our transponders were mounted on the surface panels fairly near the points on the reflector support structure that W-Y Wong computed, but some effects of the deflections of the panel sub-structure are not allowed for in the computations.

We summarize the results of the comparison as follows:

(i) The agreement in shape of the measured and computed curves is excellent.

(ii) The telescope behaves as a symmetric structure with respect to east and west movements in hour angle. The observed asymmetry is due to our offset mounting of the T/R box and shows, both in measurement and computation, surprisingly large effects.

(iii) We have found no major jumps or hysteresis effects in the behavior of the telescope over the hour-angle and declination ranges we have used.

(iv) We believe the numerical agreement between computation and measurement is also good. It is possible (but we cannot confirm this easily) that the differences are due to the differences between our actual mounting points for the transponders and the structural points computed by W-Y Wong.

8.0 References

(1) "Antenna Measuring Instrument," John M. Payne, Electronics Division Internal Report No. 98 (1970).

(2) "A Microwave Method for Checking Precision Antennas," M.I.T. Memorandum 46L-0023 (1962).

(3) "The Phase Adjustment of Large Antennas," G. Swarup and K. S. Yang, <u>IRE Transactions on Antennas and Propagation</u>, AP-9, 75-81 (1961).

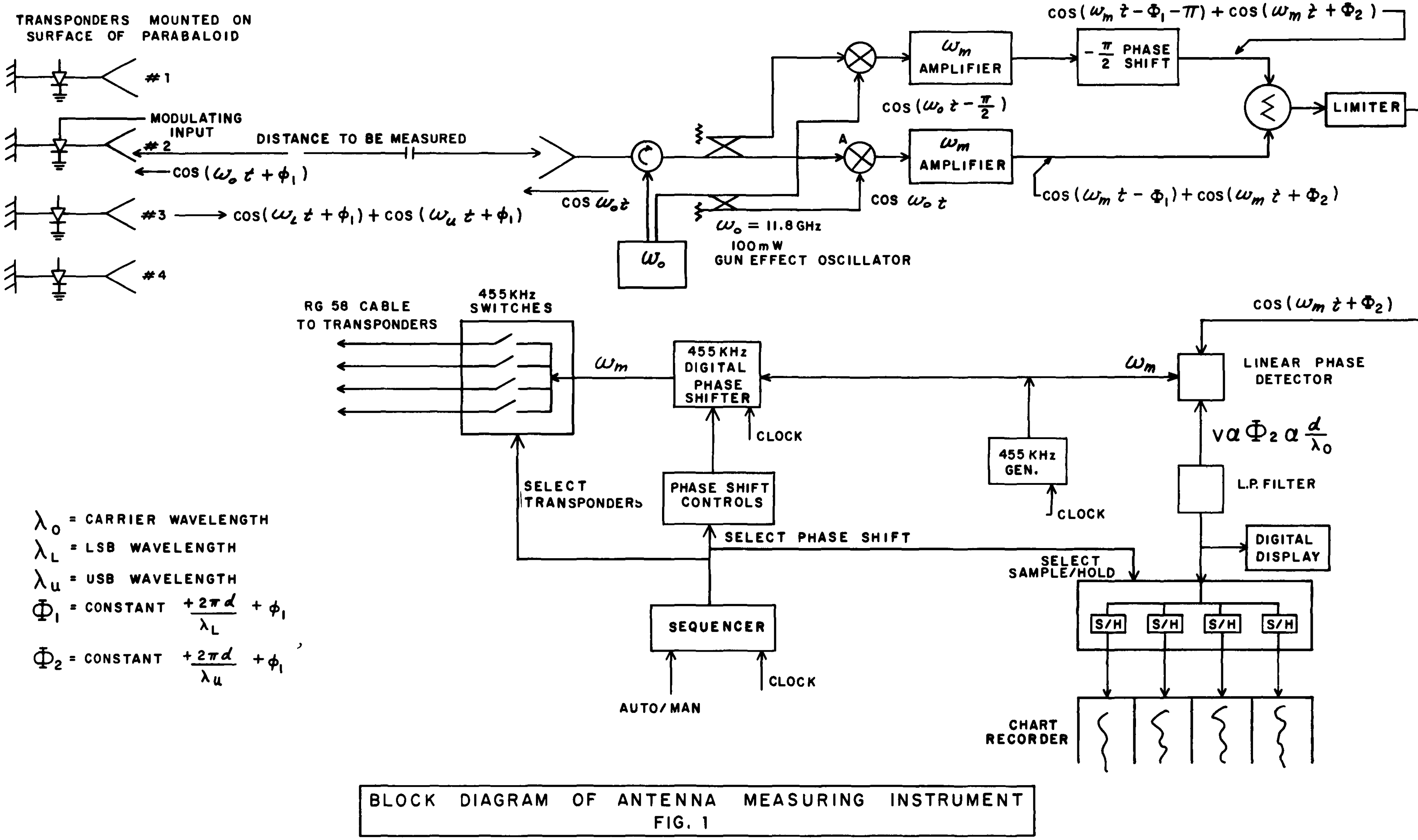

Figure 1 — Block Diagram of Antenna Measuring Instrument

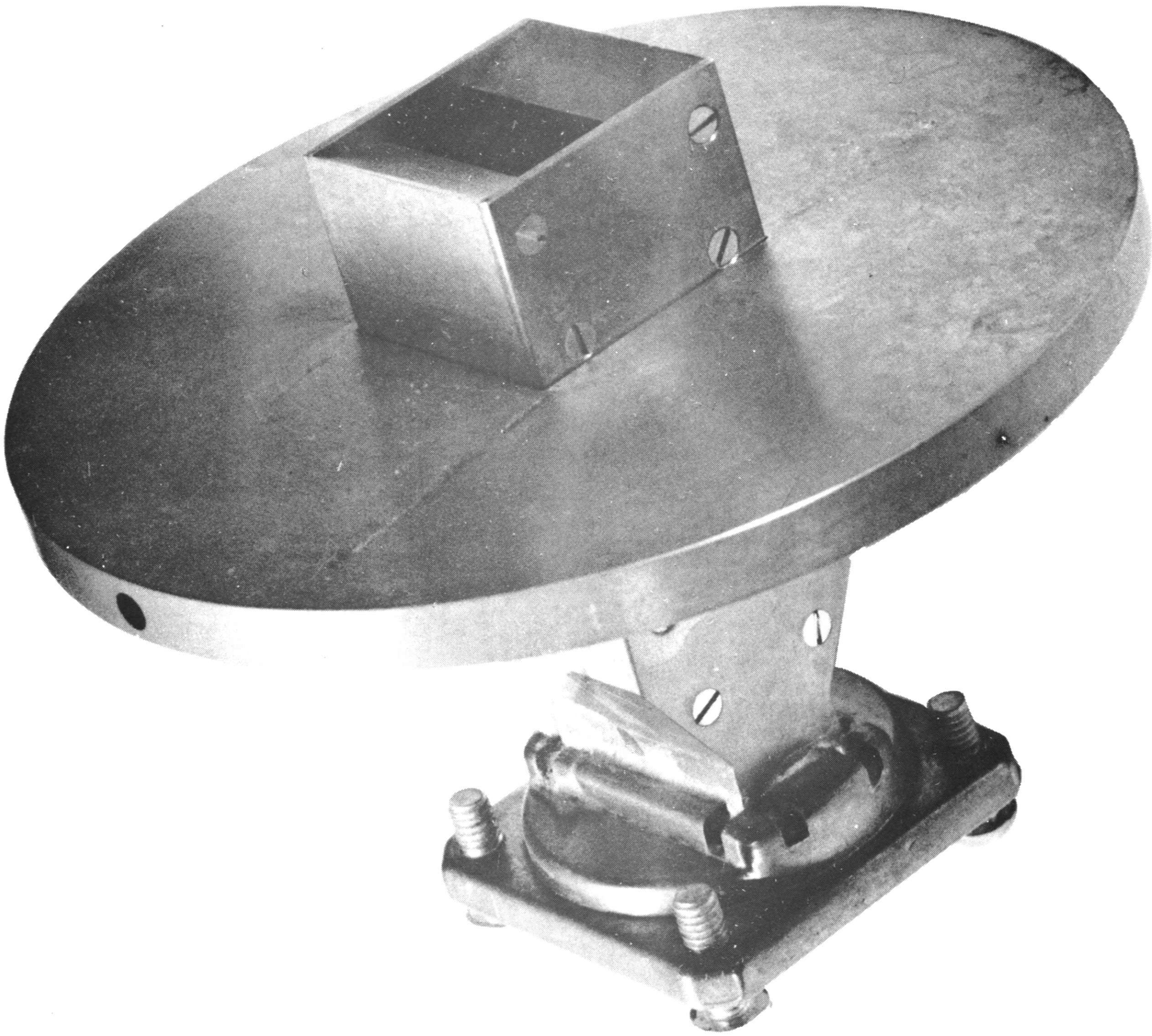

Figure 2 — Feed Horn

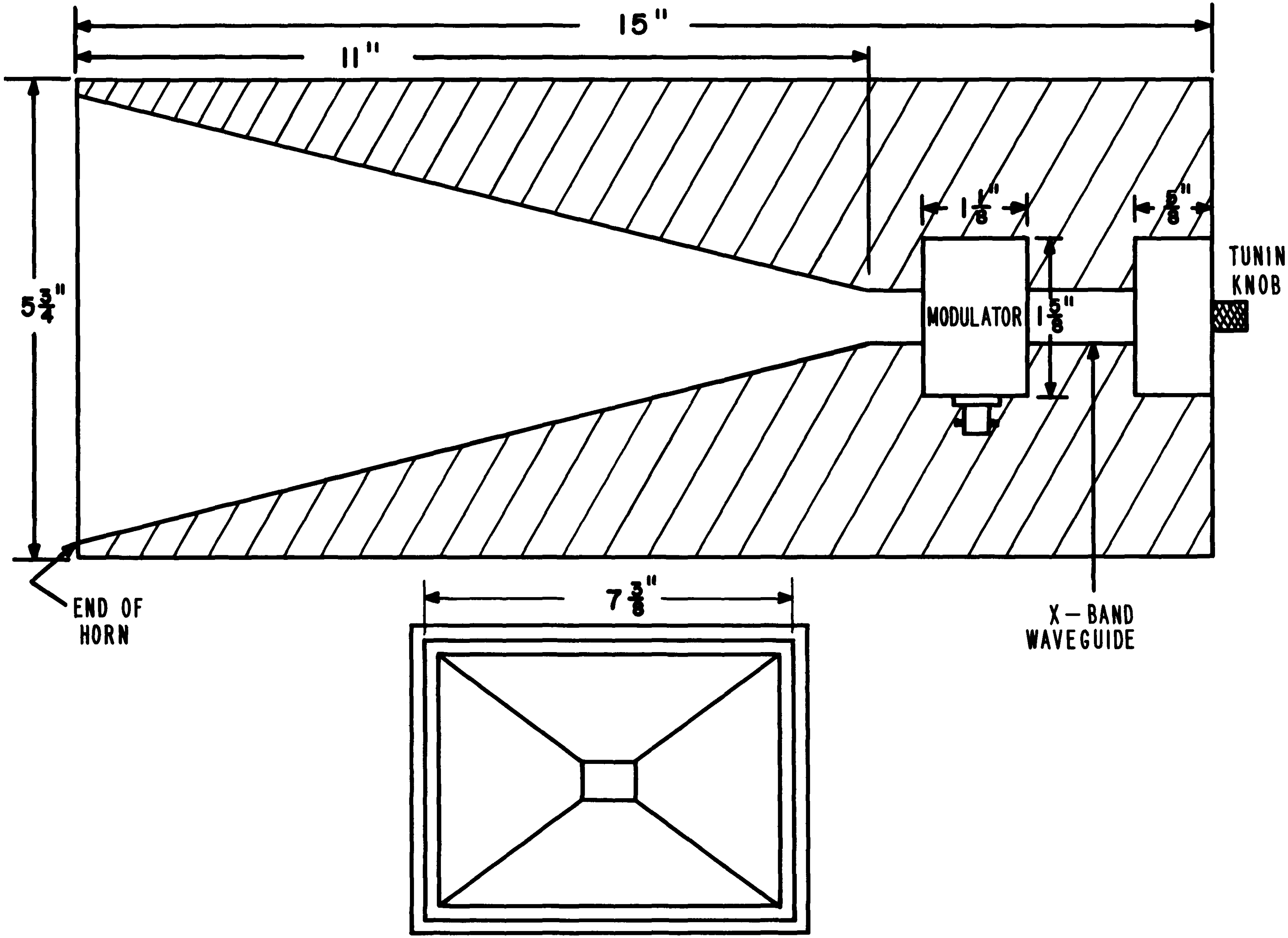

Figure 3 — Transponder

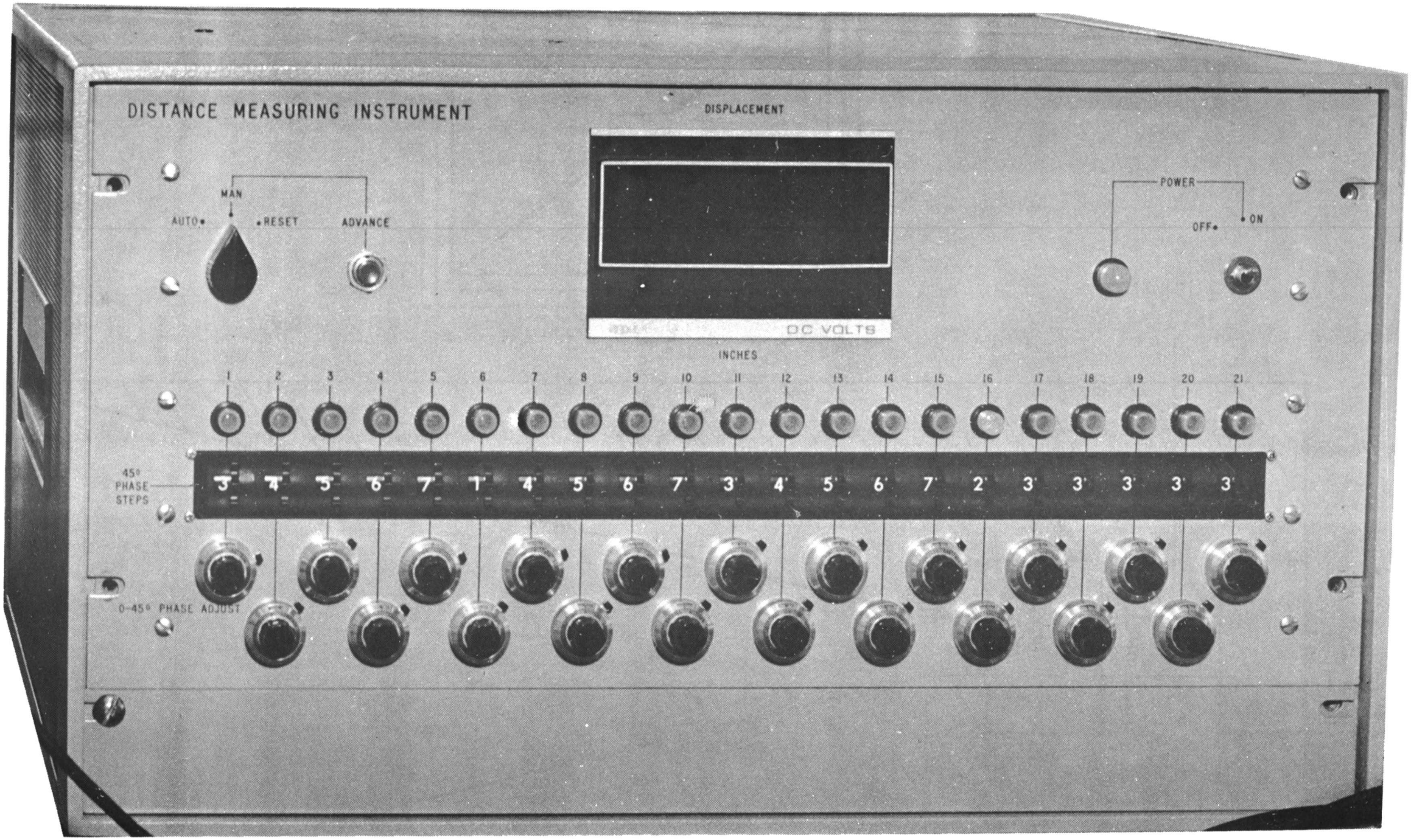

Figure 4 — The Control and Display Unit

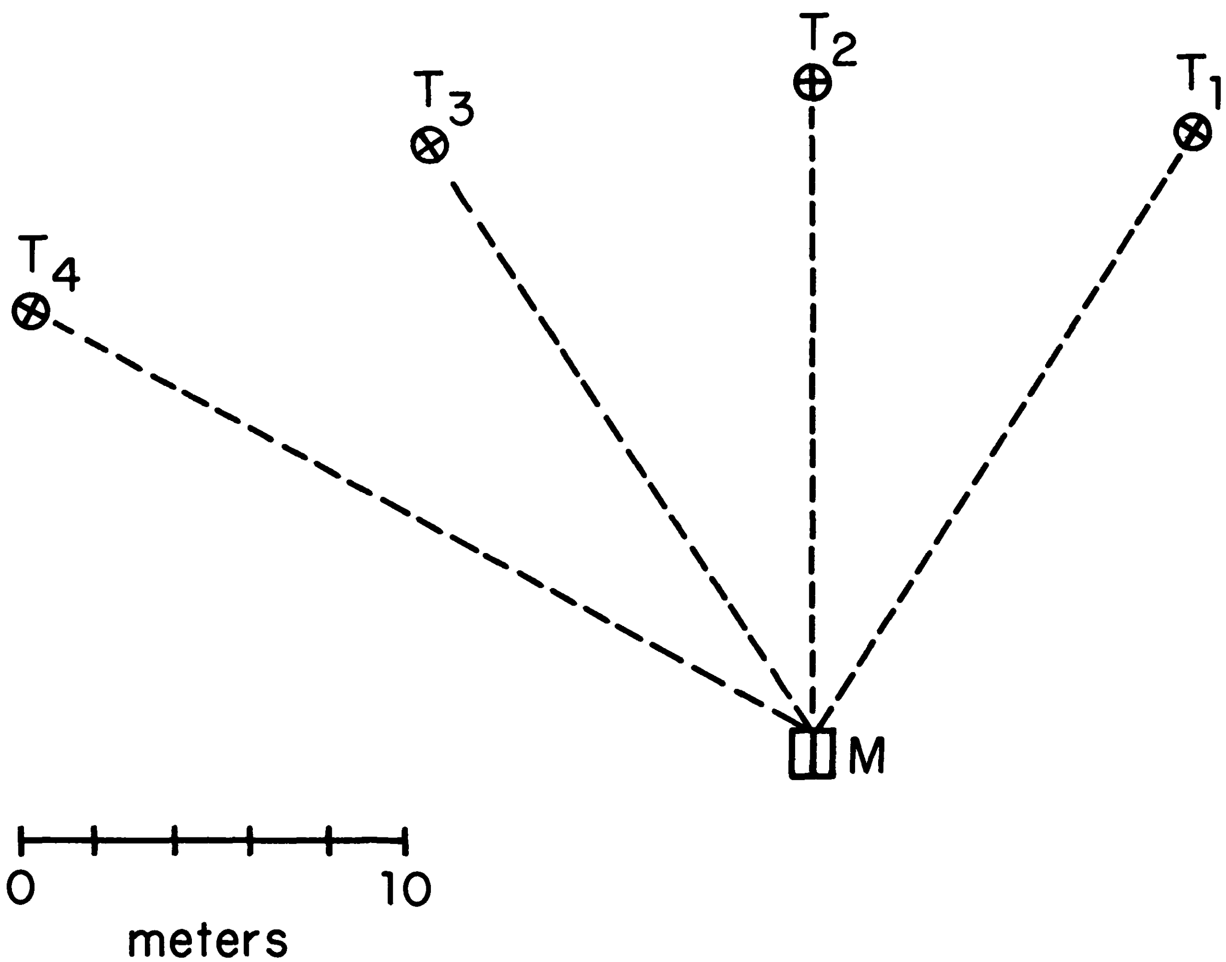

Figure 5 — Layout on the Ground of Measuring Instrument (M) and Transponders (T)

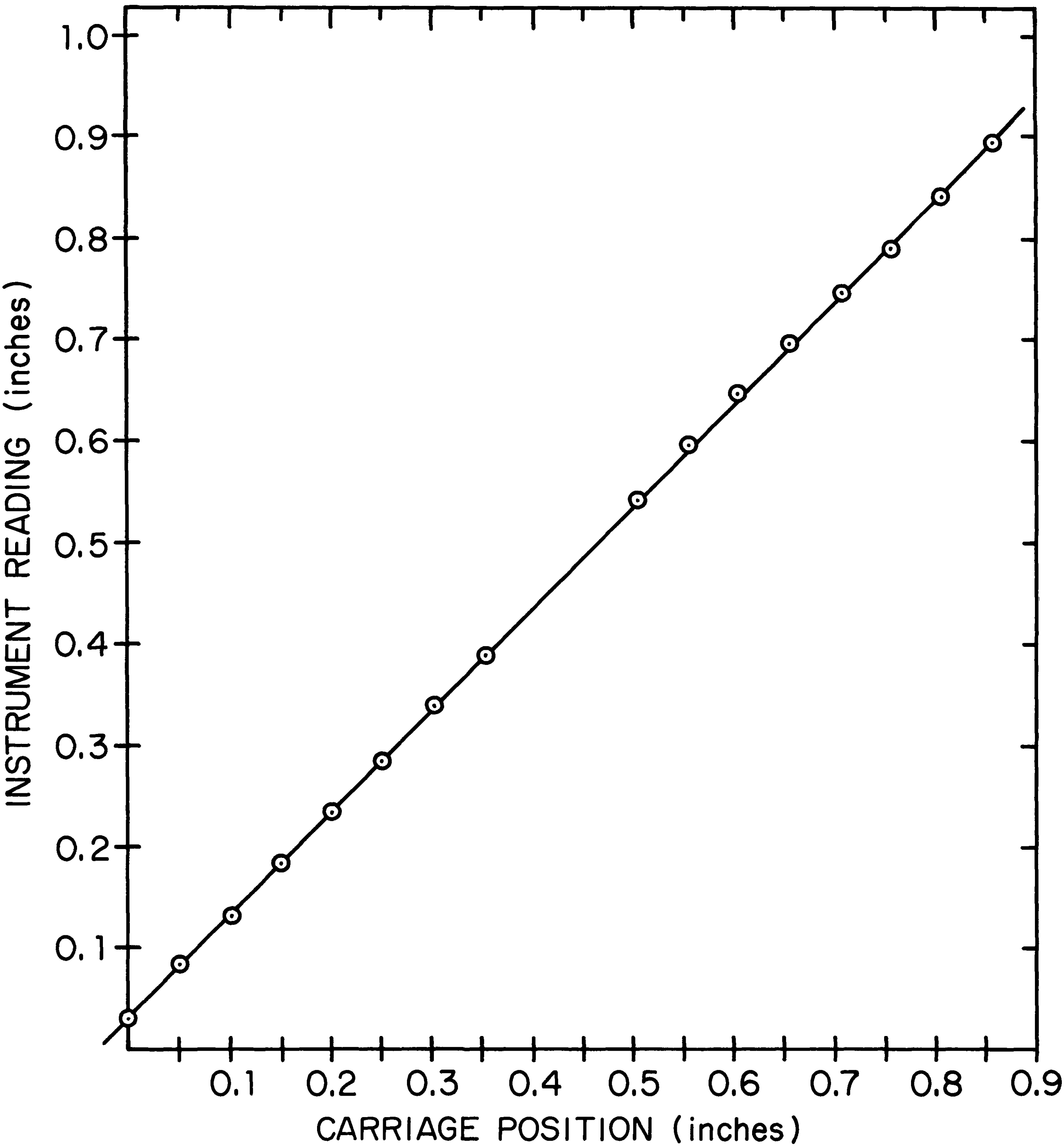

Figure 6 — Instrument Reading Plotted Against Carriage Position

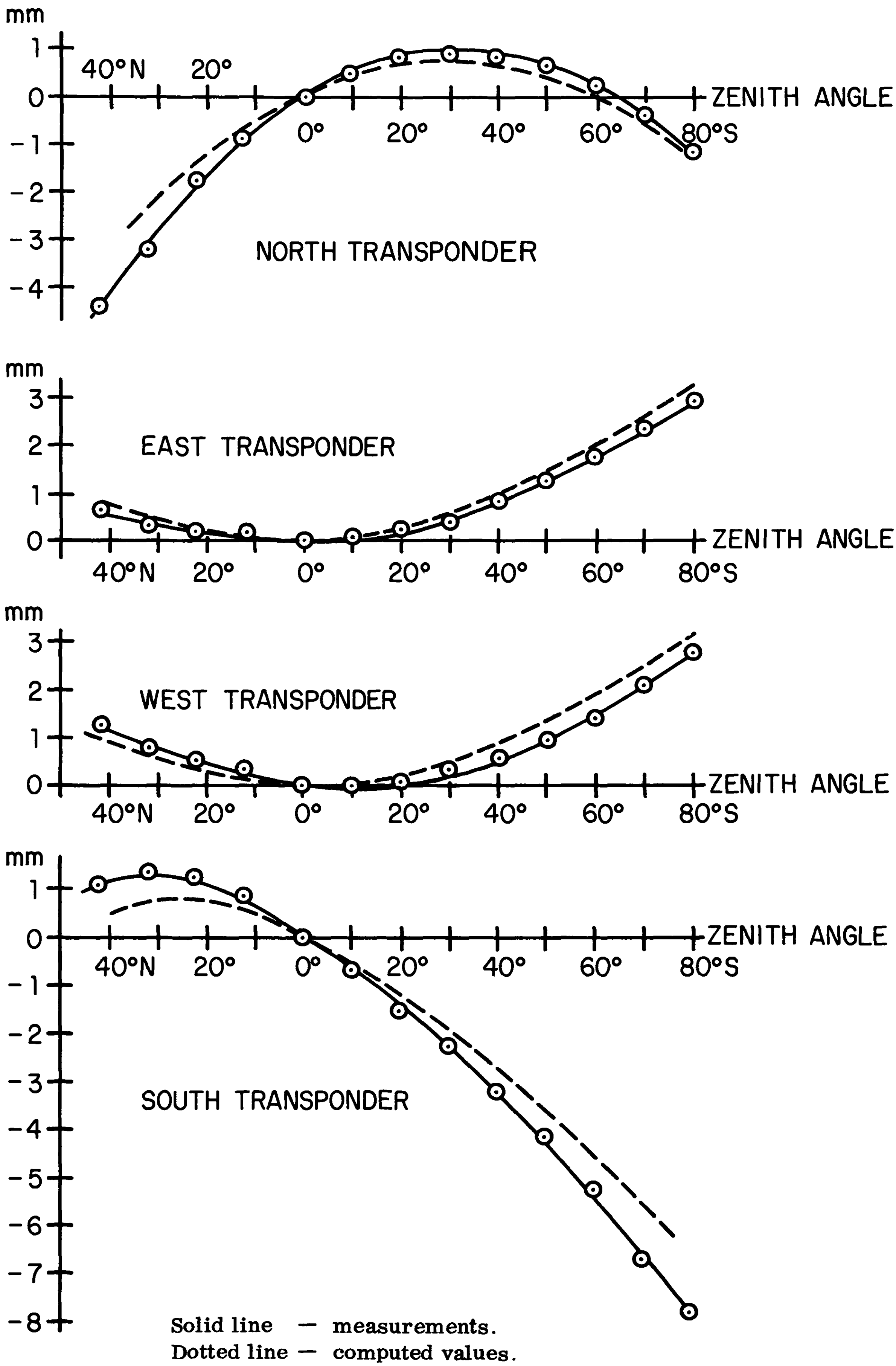

Figure 7 — Distance Changes to Transponders as Zenith Angle Changes at H.A. = 0

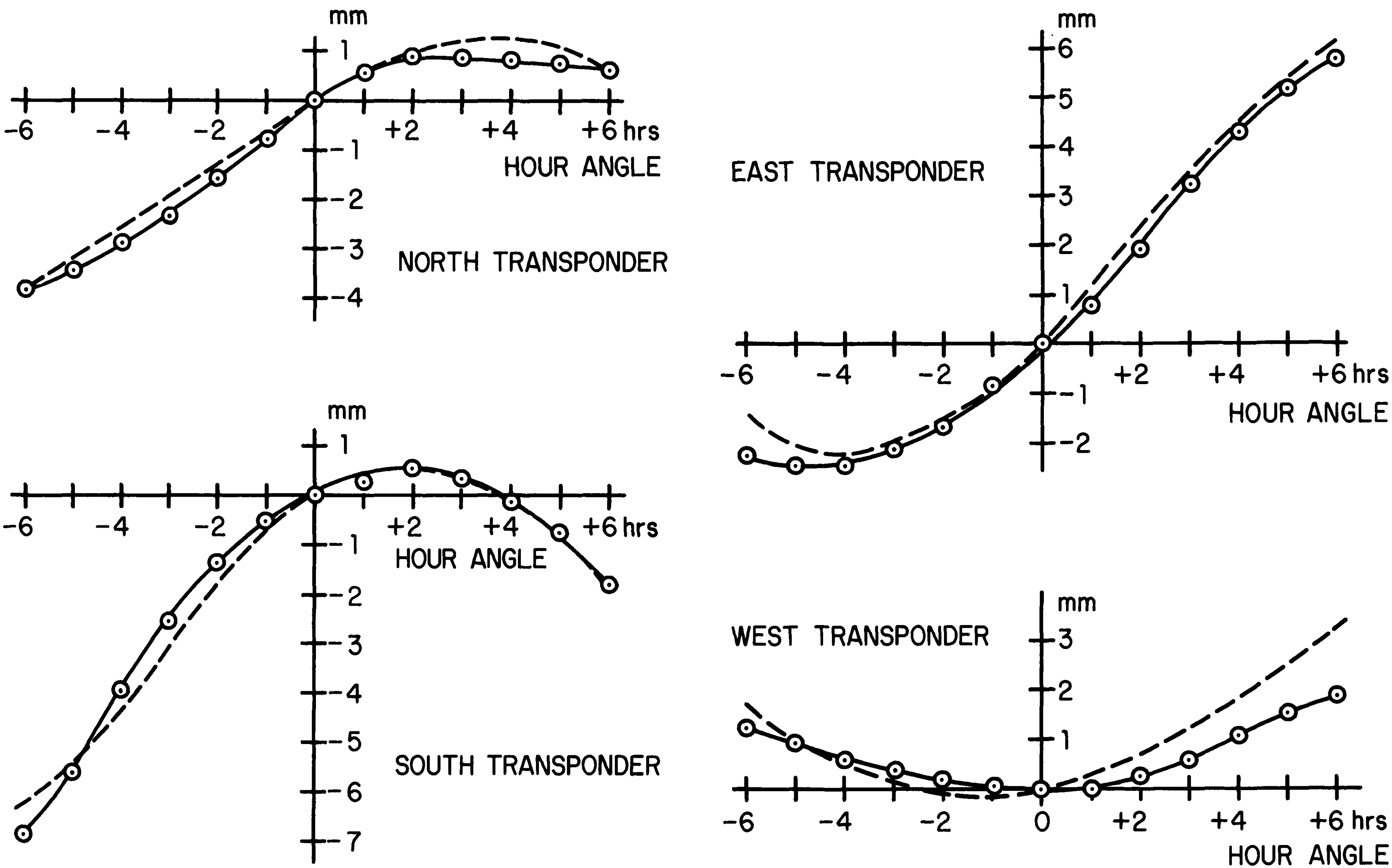

Figure 8 — Distance Changes to Transponders as Hour Angle Changes at a Fixed Declination of +38° 26'

Solid line — measurements.
Dotted line — computed values.