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AN ANTENNA PROGRAMMER USING PIN INSERTS FOR FOLLOWING SATELLITES

J. R. KENNEY

OTTAWA

MAY 1965

ABSTRACT

A system is described for programming a directional antenna to follow an artificial earth satellite as it moves across the sky. Programming is accomplished by inserting small pins, a pair for each minute of the pass, into appropriate holes in an azimuth circle and an elevation circle. This basic system is shown to be adequate for the reception of cloud-cover pictures from meteorological satellites carrying the new Automatic Picture Transmission system. It is not adequate, however, for the more stringent requirements of a Satellite Tracking and Data Acquisition Station. To meet these requirements, interpolation circuits are described which increase the pointing accuracy, without necessitating an increase in the number of inserted pins.

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AN ANTENNA PROGRAMMER USING PIN INSERTS FOR FOLLOWING SATELLITES

- J.R. Kenney -

INTRODUCTION

Since the advent of the United States Weather Satellites with APT (Automatic Picture Transmission) capabilities, many agencies other than regular tracking stations now have a requirement to receive telemetry signals from satellites. For reliable APT reception, directional antennas with 10 to 13 db of gain are used, the half-power beamwidth of such antennas being 30 to 40 degrees. The motion required of a directional antenna to follow a typical weather satellite precisely can be seen in Figs. 1 and 2. A satellite with a circular orbit at an altitude of 450 nautical miles was assumed for these curves which show elevation and azimuth from Ottawa, Canada, as a function of time for a series of equator crossings.

From the curve for the overhead pass in Fig. 1 it can be seen that the maximum angular velocity with respect to the surface of the earth, approaches 25° per minute. It follows, therefore, that for the 30° to 40° beamwidth antennas presently used for APT, positioning of the antenna once a minute should be adequate to keep the satellite within the half-power beamwidth of the antenna for almost all of the time. The exceptions occur when conditions require high azimuthal velocities; i.e., for a brief time in the middle of an overhead or nearly overhead pass, with an antenna limited to 90° in elevation movement. However, the distance to the satellite is a minimum at such times, and a greater pointing error can usually be tolerated. Once-a-minute positioning of the antenna can be done manually using predicted azimuth and elevation angles versus time, but it has been found that the full attention of the operator is required during the pass, in spite of the intermittent nature of the operation. For many of the agencies now interested in satellite tracking, however, it is advantageous to keep manpower requirements to a minimum. An antenna programmer helps in this respect in that it enables an operator to program the antenna beforehand from predicted "look" angles, and the same operator is then available for other duties during the pass. At the time that this project was initiated, no suitable programmer was available commercially, but one had been developed by the Defence Research Board of Canada for tracking the Alouette satellite. This system consists of about 60 ten-turn potentiometers, one for each half-minute of the program time, for both azimuth and elevation. These potentiometers are set before each pass to positions corresponding to the azimuth and elevation angles required for every half-minute of the pass. Our proposal was thought to be more easily programmed, and possibly less subject to errors in programming.

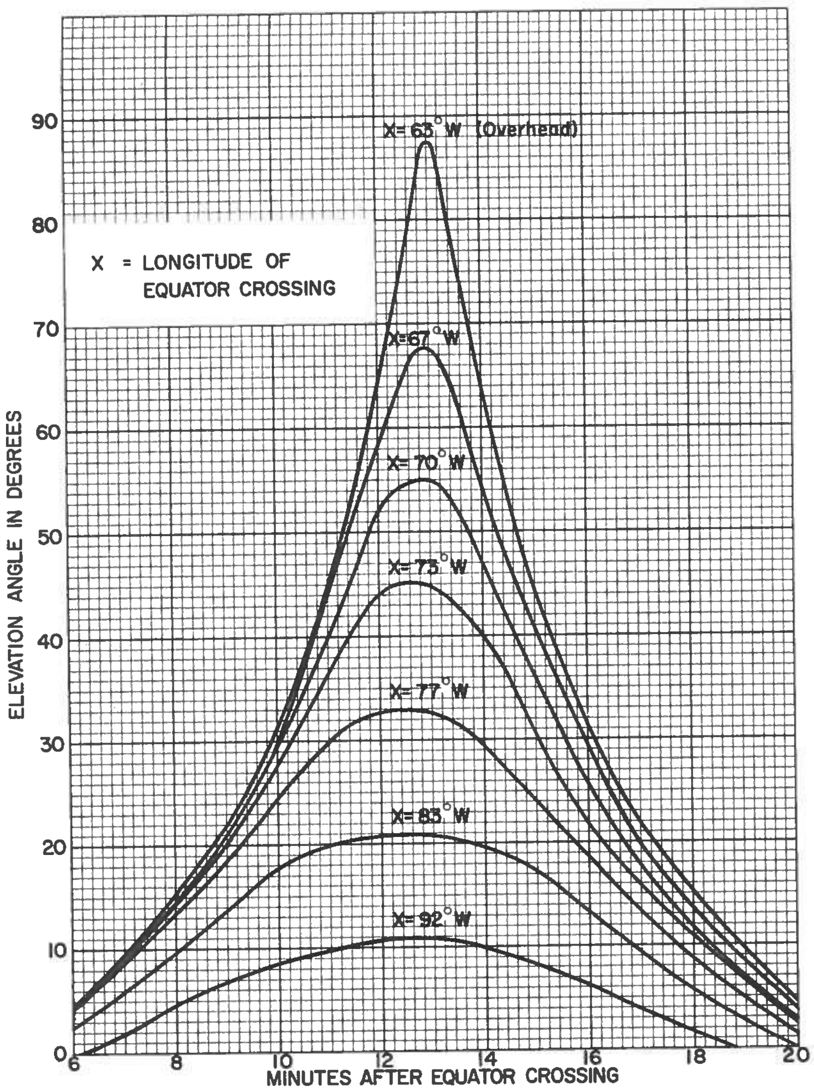


Fig. 1 Elevation versus time after equator-crossing for a typical meteorological satellite

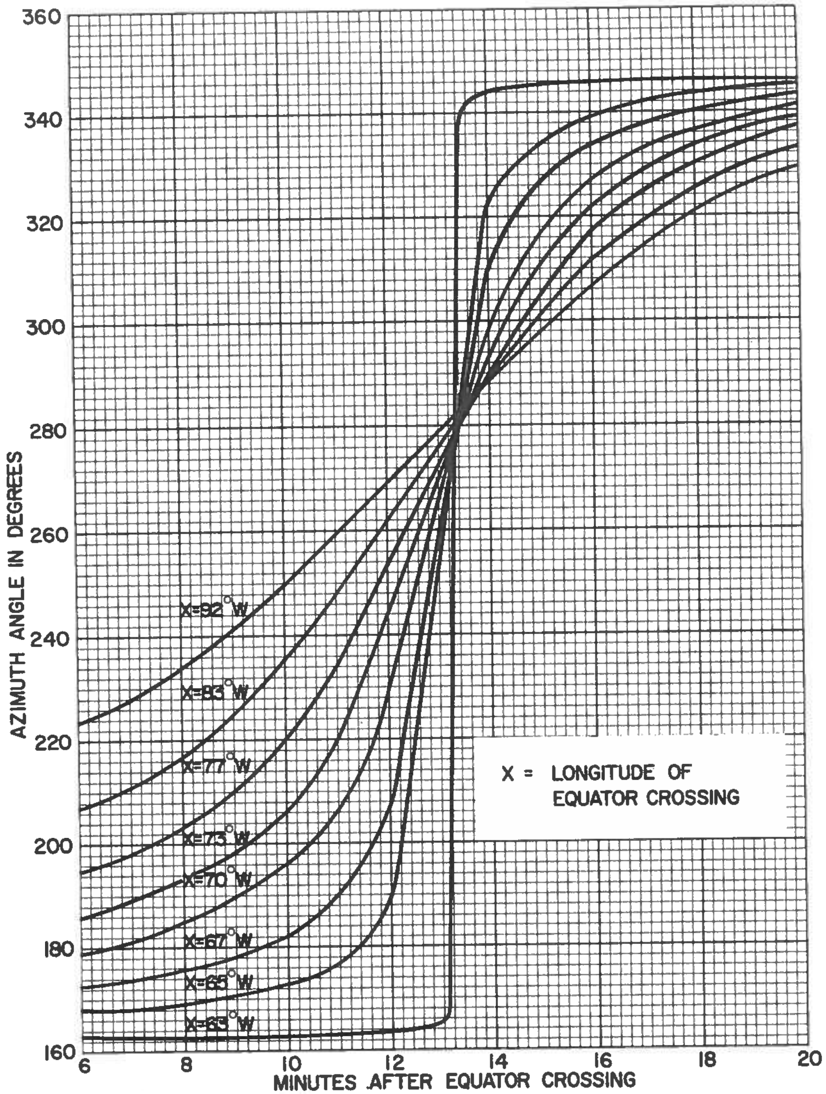


Fig. 2 Azimuth versus time after equator-crossing for a typical meteorological satellite

Receiving site: Ottawa, Canada, Satellite altitude: 450 nautical miles Satellite inclination: 81.3° retrograde

The antenna programmer described in this report was used for APT reception from both the Tiros VIII and Nimbus I satellites. Since that time, the programmer has been modified to decrease the pointing error so that it may be used with the narrower-beam antennas that have now been developed elsewhere for APT reception. Also, because the National Research Council of Canada is responsible for the operation of the Satellite Tracking and Data Acquisition Station (STADAN) at St. John's, Newfoundland, the possibility of adapting the programmer to the more stringent requirements of a STADAN station was investigated. To meet these requirements, interpolation circuits were added to the APT antenna programmer. The system was tested with an antenna simulator using computed "look" angles for several passes with high angular velocities.

An overall view of the programmer is shown in Plate I. The azimuth and elevation circles are Bakelite rings, 9 inches in inside diameter and one-half inch thick. In these rings holes are drilled every 2° over the required range of operation; i.e., from 0° to 360° on the azimuth ring and from 0° to 90° on the elevation ring. For antenna pedestals with a capability of 180° of movement in elevation, the holes in the elevation ring would be extended to 180°. The holes are of such size that 3/32" diameter steel pins can be easily inserted and removed. At the expense of larger circles and smaller pins (1/16" diameter) the holes may be drilled for every degree.

AZIMUTH PROGRAMMER

First consider the azimuth ring with its single circle of holes from 0° to 360°. From the centre of this circle an arm, driven by a small motor through a slipping clutch, extends out almost to the ring (Plate II). On the arm, an electromagnet operates a spring-loaded push-rod which extends from the arm out to the holes. When the electromagnet is not energized, the push-rod extends just far enough to engage the inserted pins. When the magnet is energized, the rod is pulled back and the arm can move past a pin. With the motor driving the arm running continuously, the arm can be made to advance from one pin to the next every minute by pulsing the electromagnet once a minute. Slip-rings are provided for connections to the azimuth arm. In the programming, the motor is switched to either clockwise or counterclockwise rotation, as determined from the predictions and it remains that way throughout the pass, since the direction of the required azimuth advances does not change during a pass. Thus, by inserting pins in the holes corresponding to the predetermined angles for one-minute intervals, and by switching to the required direction of rotation, the arm will follow the azimuth program. The method whereby the antenna follows the arm will be discussed after consideration of the elevation programmer.

ELEVATION PROGRAMMER

In elevation, the antenna must move upward to its maximum elevation for the pass in question, and then down again. To accomplish this, a double arc of holes is drilled in the elevation circle, and two push-rods are mounted on the motor-driven arm (Plate III). By drilling the inner arc of holes deeper than the outer arc, one push-rod can be made only to engage pins inserted in the inner arc, and the other push-rod, which is longer, can ride over these pins and only engage pins inserted in the outer arc. The inner holes are therefore used to program the upward motion of the antenna with the longer push-rod held back, and the shorter one pulsed. The outer holes are used to program the downward motion, with the shorter push-rod held back, and the longer one pulsed. To reverse the motor driving the arm, and to change the push-rod functions after the maximum elevation has been reached, a special pin with a larger diameter on top is inserted next to the pin for the maximum elevation, on the inner arc. This special pin closes a pair ofcontacts on the arm, and these in turn, through a self-holding relay, reverse the motor and the push-rod functions.

For both the azimuth and elevation arms, the first pulse to permit the arms to advance occurs one-half minute after the programmer start, and thereafter at one-minute intervals. In this way the step-function positioning of the antenna lags behind the satellite position just before a move, and leads it by about the same amount just after a move.

ANTENNA-FOLLOWING SYSTEM

Once the azimuth and elevation arms on the programmer have been made to follow the required program, any suitable servo system can be used to position the antenna. However, many of the available antenna systems for APT reception, as well as the STADAN telemetry system, have induction motors with speed-reducers to drive the antenna at about 1 rpm and for these a simple on-off control must be used. These antenna systems invariably have synchro repeaters to indicate the azimuth and elevation angles, and the control system employed in the programmer uses these indicators in a photoelectric system. The synchro repeaters are mounted behind the azimuth and elevation circles, with their shafts concentric with the tubular shafts of the azimuth and elevation arms. The repeater shafts are extended out through these hollow shafts towards the front, and on each shaft there is mounted in place of the pointer, a light-weight disc of sheet film, with a pattern, as shown in Fig. 3, photographed onto it. Two small lights are mounted on each arm under the outer rings of the disc, and above the lights, with the disc in between, the two photodiodes are mounted. The photo-diodes operate relays which, in turn, operate the antenna drive-motors in the direction which brings the opaque wedge on the disc towards the lights and

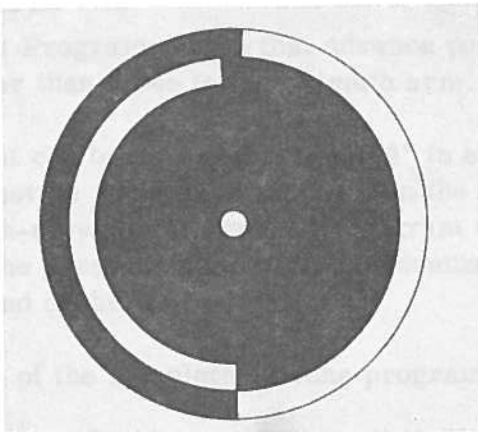


Fig. 3 Pattern of the synchro-repeater disc for the photo-electric servo system (disc diameter = 7 inches)

photodiodes. When the light is cut off from both the photodiodes, the driving voltage is removed from the antenna drive-motor, and the antenna coasts to a stop. The opaque wedge is made twice as wide as the coasting angle of the antenna so that the antenna stops with the wedge centred with respect to the lights and photodiodes. However, the coasting angle of the antenna must be kept small if the antenna is to respond to small changes in angle.

TIME PROGRAMMER

With the system that has been described, the minimum rate of change that can be programmed is 2° per minute. For most satellite passes no slower rate is required, but for overhead passes with an antenna limited to 90° in elevation movement, the azimuth may be required to remain unchanged for almost half the pass. To achieve this, a Time Programmer was added to the system, and it is shown at the top of Plate I.

This unit consists of a simple electric clock driven by the same motor which generates the arm-advance pulses. A single hand on the clock makes one revolution in 30 minutes, which is a longer period than the reception time for all but very high orbits. Holes are drilled around the clock for every minute and a wiper on the hand makes contact with pins that may be inserted in these holes. When contact is made by the wiper on the hand, the advance pulse for that minute is suppressed to the azimuth arm. If, for example, it is noted in programming that no change in azimuth is required in the next minute, the pin is placed in the hole for that minute on the Time Programmer rather than in the azimuth circle.

A situation of lesser importance arises for passes in which the maximum angle of elevation is low. Then it is the elevation angle that may be required to remain unchanged for several minutes. For this case a selector switch is provided on the Time Programmer so that advance pulses to the elevation arm are suppressed rather than those to the azimuth arm.

For antennas that can be moved through 180° in elevation, the Time Programmer would not be necessary, because in the cases where it is now principally used (high-elevation passes) the program could be changed to a fixed azimuth throughout the pass, with the elevation continuing up through 90° and down to 180° at the end of the pass.

A block diagram of the complete antenna programmer is shown in Fig. 4.

PROGRAMMING FOR APT

To set up the programmer it is necessary to know the azimuth and elevation angles to the satellite at one-minute intervals. For STADAN stations this information is computed at a computation centre, and relayed by teletype to the stations concerned. For stations not so supplied, the "look" angles can be computed from charts and graphs if the principal parameters of the orbit are known, as well as the times and longitudes of equator crossings. This information is supplied to participating stations by the United States Weather Bureau in Washington, D.C.

The method commonly used for stations tracking weather satellites is described in the APT user's guide [1] and is quite straightforward for orbits which can be considered circular. This method employs an azimuth-equidistant projection map of the earth centred on the North Geographic Pole for stations north of the equator. Centred on the station concerned is a tracking diagram which enables the azimuth and great circle arc distances to be determined for any point within 2000 miles of the station. The horizon distance for the satellite can also be determined from available tables or graphs, and the "circle" representing this distance from the station is accentuated on the tracking diagram. Pivoted at the Pole on the map is a transparent overlay, on which the ground track of the satellite is drawn with minute time intervals marked on the track referenced to the equator crossing.

In practice, the overlay is turned so that the track crosses the equator at the required longitude for the pass in question. If the track cuts the horizon circle, the pass can be received. For the interval during which the satellite track is within the horizon circle, the azimuth and great circle arc distances as a function of time are determined from the tracking diagram. Knowing the satellite altitude, the elevation angles can be determined from the great circle arc lengths. Rather than go through this procedure for every pass, tables can be made up for a series of equator-crossings which bring the satellite within range. The equator-crossing increment for these tables depends upon how rapidly the azimuth and

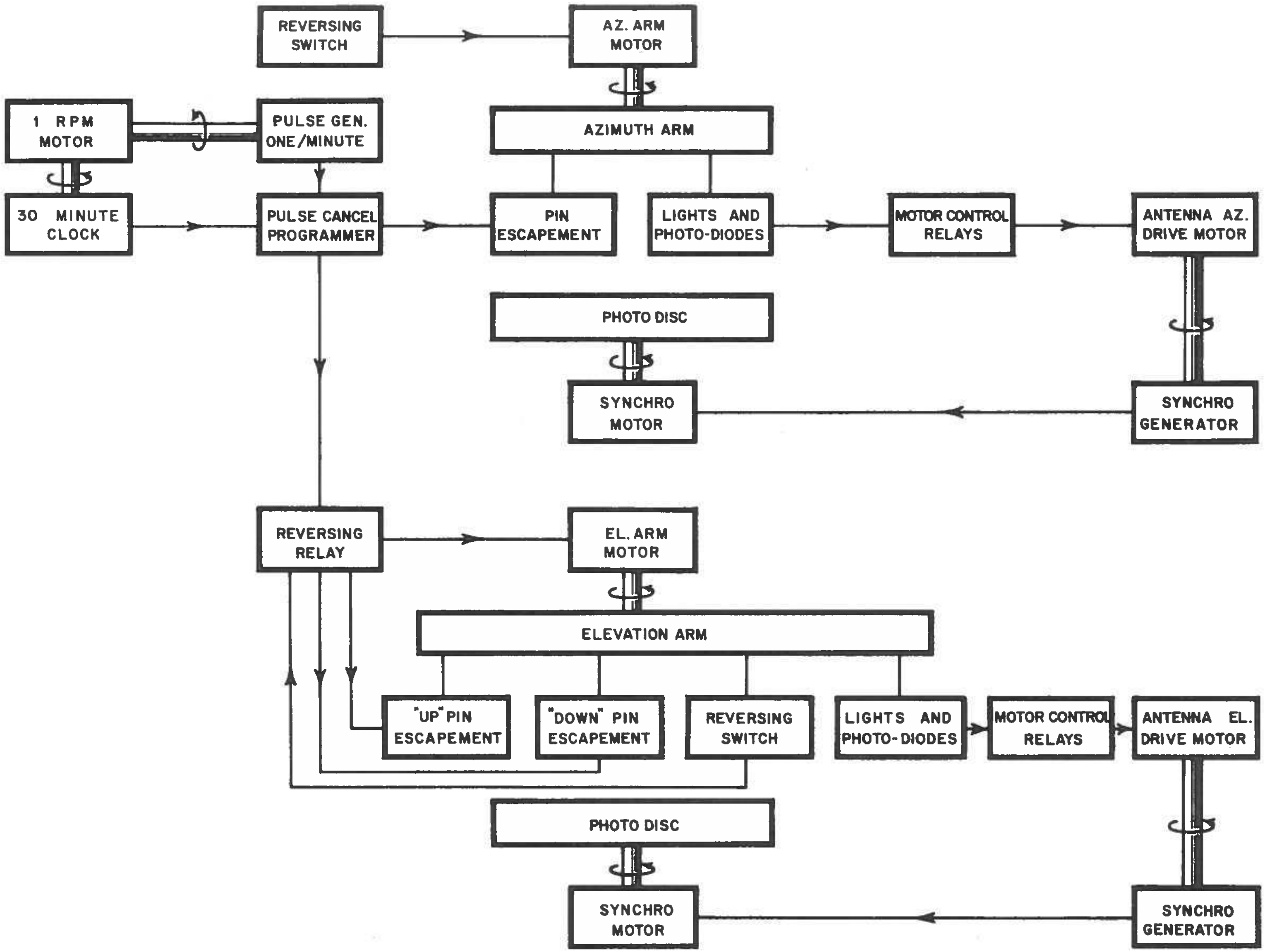


Fig. 4 Block diagram of Antenna Programmer

elevation functions change as the equator-crossing varies. Five-degree increments are adequate, except in the region of equator-crossings which results in high-elevation passes; i.e., above 60°. Two-degree increments are then adequate, except for a few degrees on each side of the equator-crossing for an overhead pass. Here, one-degree increments would be preferable.

For every equator-crossing tabulated, the time from equator-crossing to the station's horizon is also determined from the tracking board, and noted on the tables. With a knowledge of the time and longitude of the equator-crossing of the pass to be received, the antenna can then be programmed from the tables.

To program for azimuth, the equator-crossing of the pass is noted, and the table for the nearest tabulated equator-crossing is referred to. The pins are then inserted in the holes in the azimuth circle as indicated in the table. During this procedure it becomes obvious to the programmer whether the azimuth changes clockwise or counterclockwise during the pass, and the azimuth direction switch is thrown accordingly. If, in this procedure, it is noted that no change is required in the next minute, the pin is placed in that minute on the Time Programmer, and the selector switch is turned to "Azimuth Program". Thus, for each minute of the pass, an azimuth pin must be inserted either in the azimuth circle or in the clock circle.

To program for elevation from the table, pins are again inserted in the indicated holes, the inner arc of holes being used for the upward motion. When the maximum angle has been reached, the reversing pin is inserted next to the maximum elevation pin; the pins for the downward motion are then inserted in the outer arc of holes. If the Time Programmer has not been used in the azimuth program, it can be used to prevent an advance in elevation by inserting a pin in the hole for the appropriate minute, and switching to "Elevation Program." Finally, the time interval from equator-crossing until the satellite comes over the station's horizon is noted from the table. This time interval is added to the known time of equator-crossing to determine the programmer starting time.

MULTIPLE PROGRAMMING

Although the full potential of APT depends upon its immediate availability to meteorologists, nevertheless a situation might arise in which it is desirable to receive a series of passes with automatic turn-on of the equipment. An investigation was therefore conducted to determine the feasibility of adapting the pin-insert programmer to multiple programming.

This could be done by an extension of the Elevation Programmer, in which a double arc of holes is used, with a means of selecting whether the inner pins or the outer pins will be "read". If this principle were extended to handle three programs, three full circles of holes would be required on the azimuth ring, and six arcs of holes on the elevation ring. The requirement for a separate push-rod for each circle or arc of holes would result in mechanical complication, and so an alternative was tried, using the Elevation Programmer for the test.

In the modification, one push-rod was made to engage pins in both the inner and outer arcs of holes, and two phosphor-bronze wipers were attached to the programmer arm. One wiper is positioned so that it makes contact with pins inserted in the inner arc, but by bending, it can pass by inserted pins. The second wiper is positioned so that it performs in a similar manner on the outer arc. In operation, only one of the wipers is switched into the circuit at a time, depending upon the arc of holes being "read". When it is time for the arm to advance, the push-rod is pulled back, and, in order to avoid pins in the other arc of holes, it stays back until the pertinent wiper makes contact with a pin. The push-rod is then released to stop the arm at the position of the pin in question.

The tests indicate that multiple programming can be achieved without a multiplicity of push-rods, and indeed, it is possible that the arm could be stopped in time with a magnetic clutch and brake combination actuated by the wiper action, without the need of a push-rod at all.

TWO-STEP INTERPOLATION

One of the newer antennas gaining favour for APT reception is a twin skewed Yagi Antenna, Model 2B1 PSC SY-28E26 (Telrex Laboratories, Asbury Park, N.J.) with published specifications as follows:

Gain: 16 db circular polarization
Horizontal beamwidth: 16°
Vertical beamwidth: 34°

The necessary increase in pointing accuracy of the programmer to take advantage of this antenna could be achieved by programming more often than once a minute, or by an interpolation circuit which would automatically interpolate between the once-per-minute settings.

A simple interpolation system which would be suitable for antenna pedestals with constant-speed motors was tested in the laboratory using an antenna simulator. In this system, two modifications are made to the programmer itself.

1. The azimuth and elevation rings are made of metal rather than Bakelite, so that inserted pins can be used to complete circuits through the push-rods.

2. The motors and gear trains driving the azimuth and elevation arms are selected so that the angular velocity of the arms is twice that of the antenna itself.

The programming operation is the same as before, except that the azimuth reversing pin should now be set at the angle of maximum elevation, since with two steps per minute, the antenna can be made to proceed up to this elevation, remain there for part of the minute, and then proceed down to the next minute pin.

In operation, the pulses to permit the arms to advance occur at 15 seconds after the minute. While an arm is advancing the corresponding antenna drive-motor operates, but stops when the arm hits the next pin. During this time, the antenna will have moved only one-half as far as the arm itself, because the angular velocity of the antenna is one-half that of the arm. At 45 seconds after the minute, the antenna motors are again operated, until the antenna reaches the position of the programmer arms. In this way, the antenna takes two equal steps per minute in both azimuth and elevation for every advance of the programmer arms.

Although the pointing error is reduced by approximately one-half by this interpolation, the error may still be undesirably large at the time of maximum elevation of a high-elevation pass. This error is compounded since maximum elevation of the pass does not, in general, occur at one of the programmed times, unless the programming is done with this end in view. However, this error can be reduced for high-elevation passes by an additional programming which "shapes" the top of the elevation function according to whether the maximum elevation of the pass is reached in the first 20 seconds of the minute interval, the middle 20 seconds, or the last 20 seconds.

The result of this programming, which is selected by a three-position switch, is shown in Fig. 5. Fig. 5(a) represents the situation in which the maximum elevation of the pass occurs during the first 20 seconds of the minute interval, defined by the pin positions shown, and the antenna motion follows the curve more closely if the downward motion is advanced by starting down at 30 seconds after the minute. For cases in which the maximum elevation of the pass occurs near the middle of the minute, as shown in Fig. 5(b), the antenna is made to remain at maximum elevation for 30 seconds in the middle of the minute. For the third case (Fig. 5(c)), the antenna motion is delayed so that maximum elevation is not reached until 30 seconds after the minute, and it remains there for 15 seconds before starting down.

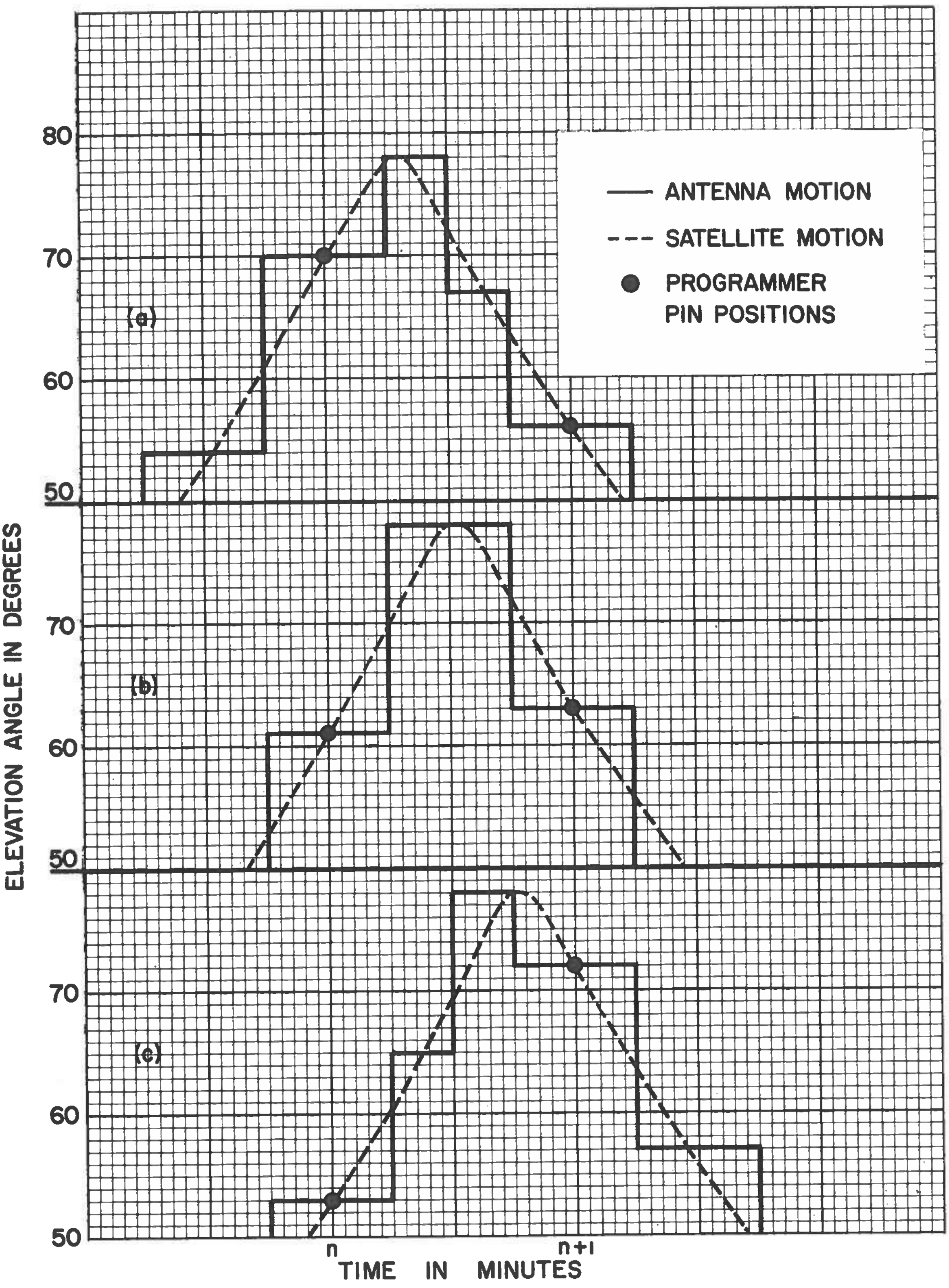


Fig. 5 Antenna motion, with a circuit to advance (a), or delay (c), the time at which maximum elevation of the antenna is reached

When it is desirable to advance or delay the top of the elevation function in this manner, it is advantageous to advance or delay the azimuth timing as well during this minute. With the same switch, the azimuth arm during this minute can be made to make the two moves at 15 seconds and 30 seconds (advanced), at 15 and 45 seconds (normal), or at 30 and 45 seconds (delayed).

Tests with the antenna simulator indicate that the two-step interpolation system would be adequate to follow typical weather satellites using the twin skewed Yagi antenna. This system, of course, depends upon the antenna speed and starting time remaining relatively constant. If this were not the case, small constant-speed motors, such as used in the antenna simulator, could follow the program, and the antenna in turn could be slaved to these motors.

INTERPOLATION SYSTEMS FOR STADAN REQUIREMENTS

The beamwidth of the telemetry antenna used at the St. John's STADAN station is 19° in both the horizontal and vertical planes. For most passes requiring telemetry reception at St. John's, the two-step interpolation system would probably be adequate. However, some of the satellites to be followed at these sites have highly elliptical orbits with a low perigee. For high-elevation passes with such a satellite near perigee, the angular velocity may be many times greater than that of a typical weather satellite. To extend the capability of the pin-insert programmer to meet these more extreme cases, three more sophisticated interpolation circuits were tested using the antenna simulator. The first is somewhat similar to the two-step interpolating system, except that the antenna takes six steps during the minute, with the time duration of each step equal to the time taken for the programmer arm to advance from one pin to the next. The second system uses an interpolating potentiometer and a d-c positioning system. A third system, which will not be described in detail, uses two stepping relays to count the angles through which the azimuth and elevation arms move to the nearest 10 degrees. These counts then determine the number of 10-degree steps taken by the antenna during the next minute.

SIX-STEP INTERPOLATION

This system, like the two-step interpolation system, requires that the azimuth and elevation rings be made of metal so that inserted pins can be used to complete circuits through the push-rods. The motors and gear trains driving the azimuth and elevation arms are selected so that the angular velocity of the arms is six times that of the antenna itself.

Consider the azimuth circuit. On the minute, the azimuth arm advances from one pin to the next. While it is advancing, a low-leakage capacitor (10μfd) is connected to the supply voltage through a 1-megohm resistor. The capacitor partially charges, and the voltage stored on it is therefore a measure of the azimuth change. At five seconds after the minute the azimuth motor in the antenna is started and a second capacitor starts to charge, the charging voltage and the time constant being the same as for the storage capacitor. When the voltage amplitude on the second capacitor reaches that of the storage capacitor, the antenna drive motor stops. The antenna drive will therefore have been energized for a time equal to the time required for the azimuth arm to make its last advance, but the antenna will have moved only one-sixth as far. The second capacitor is then discharged, and the cycle is repeated every 10 seconds throughout the minute.

The photoelectric following system is still employed. It determines the direction that the antenna must move, and also prevents the antenna from ever moving past the position of the azimuth arm. During the last five seconds of the minute, the antenna motor is energized until the antenna reaches the position of the azimuth arm.

The elevation circuit is much the same, but here again a problem arises during the minute in which maximum elevation is reached. If maximum elevation occurs between programmed times, it is difficult to have the programmer itself determine the rate required for that minute and still have the antenna proceed up to maximum elevation and down again. To overcome this, the approximate rate required during this minute is calculated quite simply from the elevation angles for the pass, and this rate is pre-set into the elevation programmer. When the elevation arm reaches the reversing pin (set at the angle of maximum elevation) the arm stops, and the pre-set rate is switched in to drive the antenna up to the position of the arm. The elevation arm then reverses direction and proceeds down to the next minute pin. The antenna again follows at the pre-set rate. At the end of this minute, normal operation is resumed. This system also would be very dependent upon the antenna speed and the starting time remaining relatively constant. It is doubtful that such would be the case under different weather conditions. However, the tests indicated that the small, synchronous motor used in the antenna simulator operates satisfactorily, and the antenna could be slaved to such a motor.

POTENTIOMETER INTERPOLATION

In this system, both the azimuth and elevation arms of the programmer are connected to the shafts of potentiometers. The voltage on the wiper of a potentiometer is therefore a measure of the angle of the corresponding programmer arm.

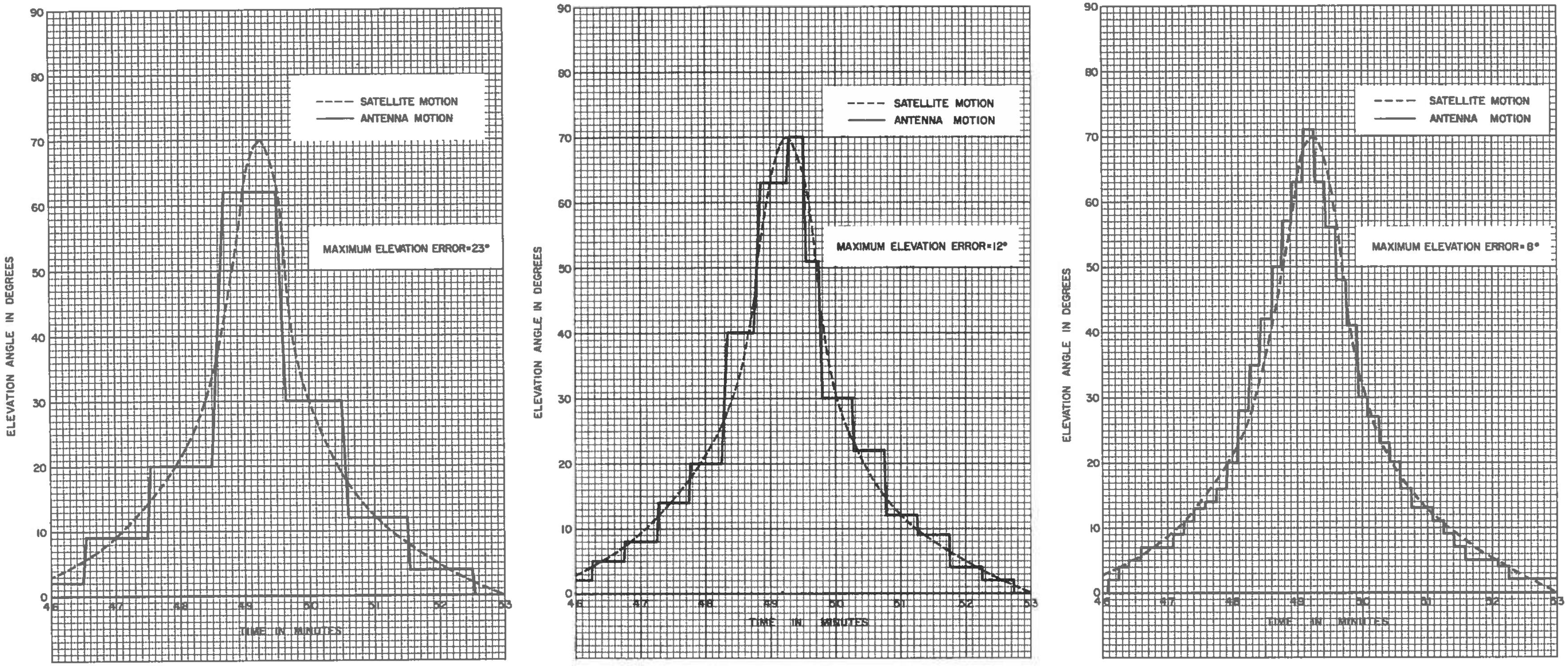
Consider the azimuth circuit. The wiper of the potentiometer is connected to one of two low-leakage capacitors, which quickly charges to the voltages of the potentiometer wiper. On the minute, the wiper is disconnected from the first capacitor, and connected to the second, and the arm moves to the next minute pin. The first capacitor therefore stores a voltage proportional to the last position of the arm, and the second capacitor charges to a voltage proportional to the new position of the arm. These voltages are applied across a linear interpolating potentiometer, through cathode followers. The wiper of this potentiometer is driven from one end to the other during the minute, and thus, the voltage on this wiper changes linearly during the minute from the voltage representing the last position of the programmer arm, to the voltage representing the new position of the arm. The voltage from this interpolating potentiometer is applied to one input of a differential amplifier, and to the other input is connected the wiper from a potentiometer driven by the azimuth drive of the antenna itself. An imbalance in the differential amplifier operates a relay which turns the antenna in the direction to bring the system into balance. The gain of the differential amplifier is adjusted to respond only to changes in angle greater than four or five degrees, to prevent hunting, and to avoid too frequent starting and stopping of the antenna.

For elevation, the system is basically the same, but once again, a difficulty arises in the region of maximum elevation with high-elevation passes, unless extra measures are taken. In the tests with the antenna simulator, the procedure for this minute is quite similar to that described for the "Six-Step Interpolation." The reversing pin is again set at the angle of maximum elevation, and pre-set potentiometers are automatically switched in to determine the rate of change of elevation during this minute.

MORE FREQUENT PROGRAMMING

Examination of the required azimuth function of high-elevation passes indicates that the azimuthal velocity may be required to change quite drastically from a low rate, to a rapid rate, and to a low rate again, all within the minute in which maximum elevation is reached. It can be shown that in some cases even perfect linear interpolation between minute points could result in effective azimuthal errors greater than the one-half beamwidth of the STADAN antenna. This is the case for one of the passes used in the simulated tests, the azimuth and elevation curves for which have been plotted in Figs. 6 and 7 from look angles supplied to the STADAN station at St. John's , Newfoundland.

The maximum angle of elevation (70°) is more than one-half the antenna beamwidth from the zenith, and so it would not normally be programmed for fixed azimuth and 180° of elevation motion. On the other hand, with perfect linear interpolation between the one-minute programmed times, the effective azimuth error would reach 30°. It appears, therefore, that in some cases for

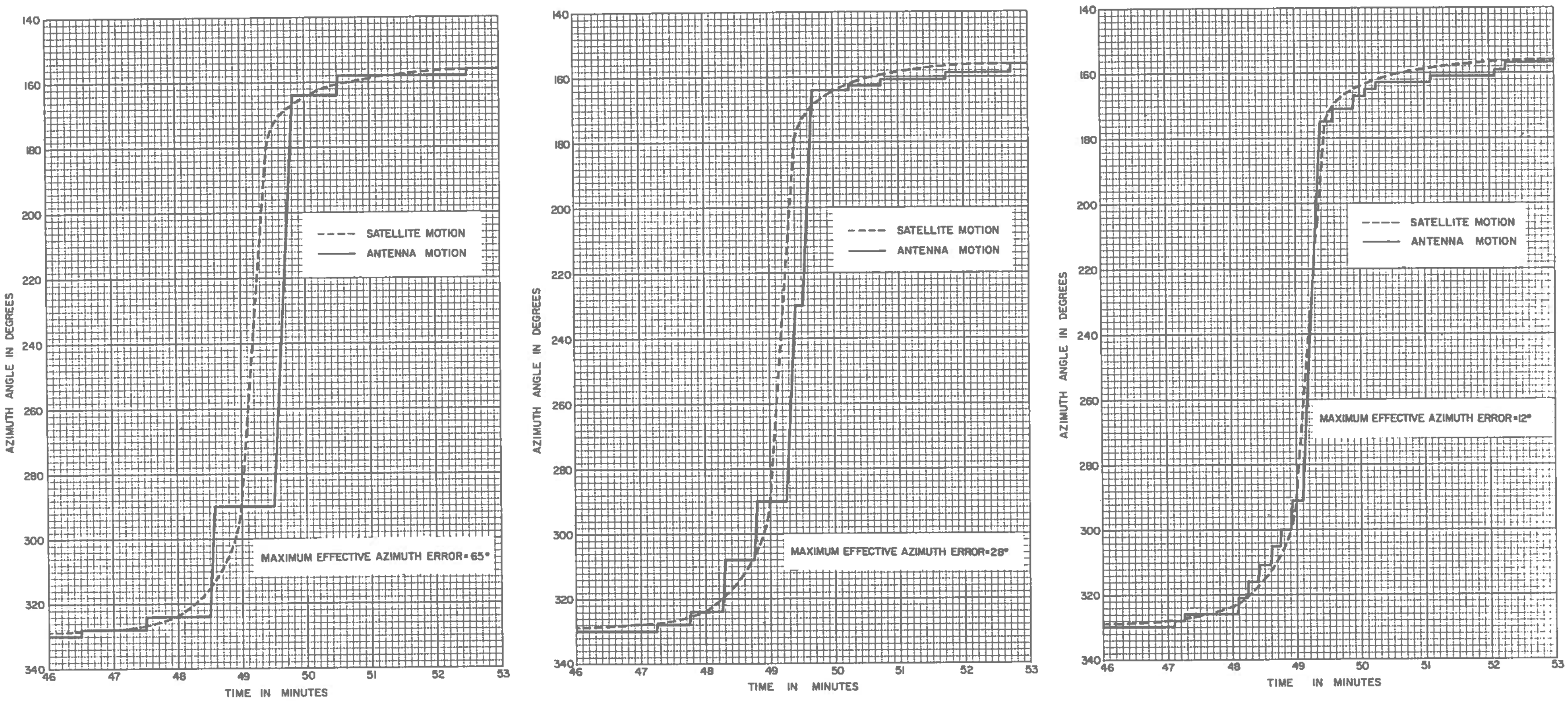


(a) Simple once-a-minute programming

(b) Two-step interpolation

(c) Six-step interpolation

Fig. 6 Antenna motion in elevation for test pass no. 3



(a) Simple once-a-minute programming

(b) Two-step interpolation

(c) Six-step interpolation

Fig. 7 Antenna motion in azimuth for test pass no. 3

the STADAN situation, the antenna must be programmed more often than once per minute during this critical minute, if continuous tracking is to be assured.

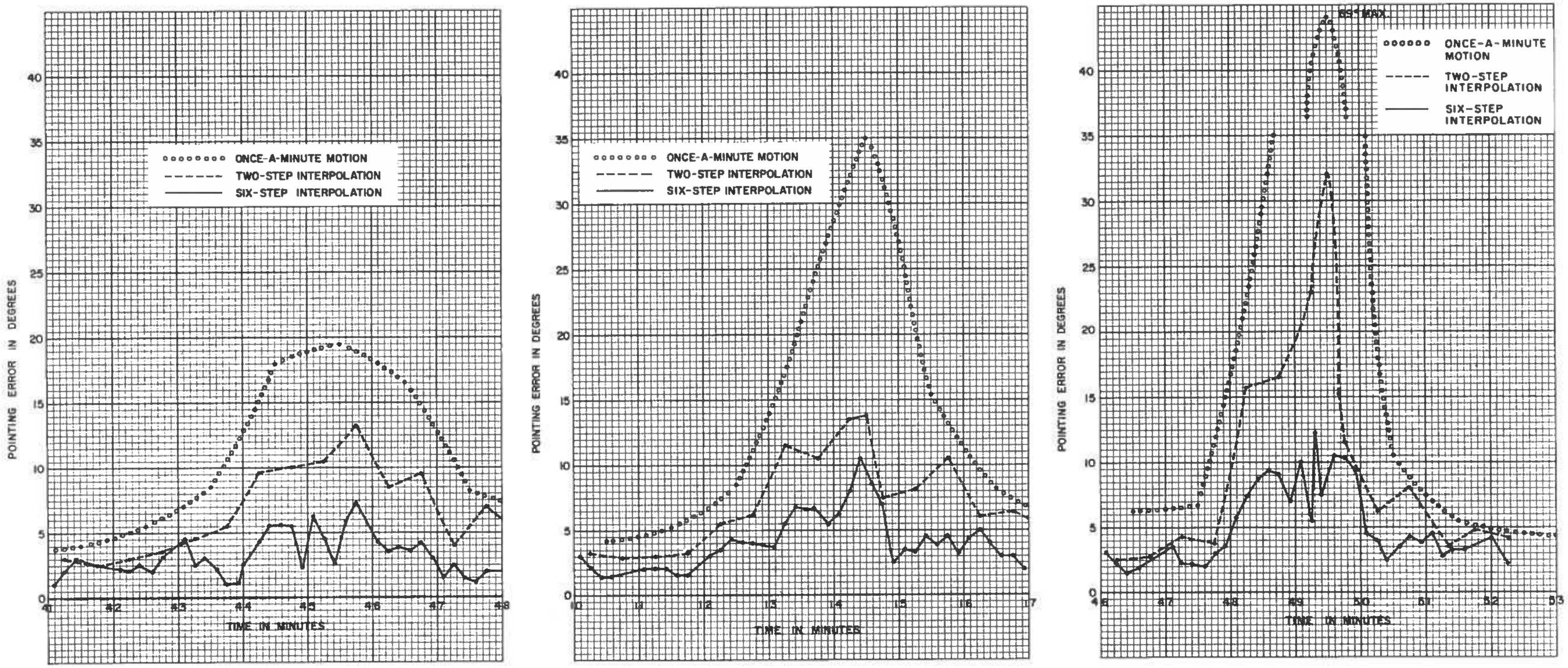
To overcome this difficulty, a system was tried in which, by throwing a switch beforehand, the antenna would advance through six pin positions during this critical minute, rather than follow a stepped, linear interpolation. When using this extra programming, therefore, six pins have to be inserted in the azimuth circle for this minute. For look angles supplied on a once-a-minute basis, the problem becomes one of deciding when this extra programming is necessary, and if so, where to place these extra pins. A simple rule depending upon maximum elevation and upon maximum angular velocity in elevation could probably be formulated to determine when the extra programming should be used. As for the location of the extra pins, plotting the azimuth-function for a few minutes before and after the critical minute, would seem to be the simplest solution. The time and azimuth when maximum elevation is reached is also provided with the once-a-minute look angles, and this point must be plotted, as well, if the azimuth function is to be properly determined. From this curve, the angles for the six extra pins can easily be found.

RESULTS AND CONCLUSIONS

The simple programmer, without interpolation circuits, was used for the reception of APT pictures from two meteorological satellites, Tiros VIII in the winter and spring of 1964, and Nimbus I in the autumn of 1964. Once-a-minute programming proved adequate, and the programming was not too involved. The various modifications to improve the pointing accuracy were tested with an antenna simulator, using high angular velocity passes selected from computed look angles for Ottawa, Ontario, and St. John's, Newfoundland. The smoothed curves of azimuth and elevation versus time for one of the passes are shown in Figs. 6 and 7, together with the step-function movement of the programmed antenna, with and without interpolation circuits. From the graphs, the pointing errors at any time can be calculated by measuring the azimuth and elevation errors, $\Delta\theta$ and $\Delta\phi$, and the elevation angle ϕ. The pointing error is then given to a first approximation by the equation:

$$\text{Approximate Pointing Error} = [(\Delta\theta \cos\phi)^2 + \Delta\phi^2]^{\frac{1}{2}}.$$

The pointing errors were calculated at the time of each step, since the errors would be greatest at these times. The error curves for this pass, and for two other test passes are shown in Fig. 8. The curves join the points of maximum error, and no attempt is made to show the variations in the error between times of the step movements. The results are summarized in Table I.



(a) Test pass no. 1

(b) Test pass no. 2

(c) Test pass no. 3

Fig. 8 Error at the time of antenna motion

TABLE I – Maximum Pointing Error with Various Interpolation Systems

Receiving Site	Satellite	Date	Maximum elevation	Maximum angular rate	Maximum Pointing Error			
					Once-a-minute	Two-step interpolation	Six-step interpolation	Potentiometer interpolation
Ottawa	ADI-E	64-11-23	80°	40°/min	20°	13°	8°	9°
Ottawa	ADI-E	64-12-08	78°	47°/min	35°	14°	11° *	9° *
St. John's		62-13-21	70°	76°/min	69°	32°	12° *	11° *

*With extra programming for azimuth during the minute of maximum elevation

From Table I it can be seen that even though simple once-a-minute programming proved adequate for APT reception with an antenna of 10-db gain, it is quite inadequate for certain passes at STADAN stations. With two-step interpolation the maximum error is reduced by approximately one-half for the test passes. This system would therefore be adequate for APT reception with the newer antennas available, but it would still be inadequate to meet all the requirements of a STADAN station. For the most severe of these requirements, even the more sophisticated interpolation circuits proved to be inadequate in the tests, unless provision is made for inserting extra programming pins in the azimuth circle during the most critical minute when maximum elevation is reached. With this provision, however, both the six-step interpolation and potentiometer interpolation proved adequate, with little difference in pointing error between the two systems. The third system that was tried, using stepping relays to count the angles through which the programmer arms move, was the least satisfactory of the three.

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1. "APT Users' Guide", Leon Goldschlak, Scientific Report No. 1, June, 1963, Allied Research Associates, Inc., Concord, Massachusetts, U.S.A.

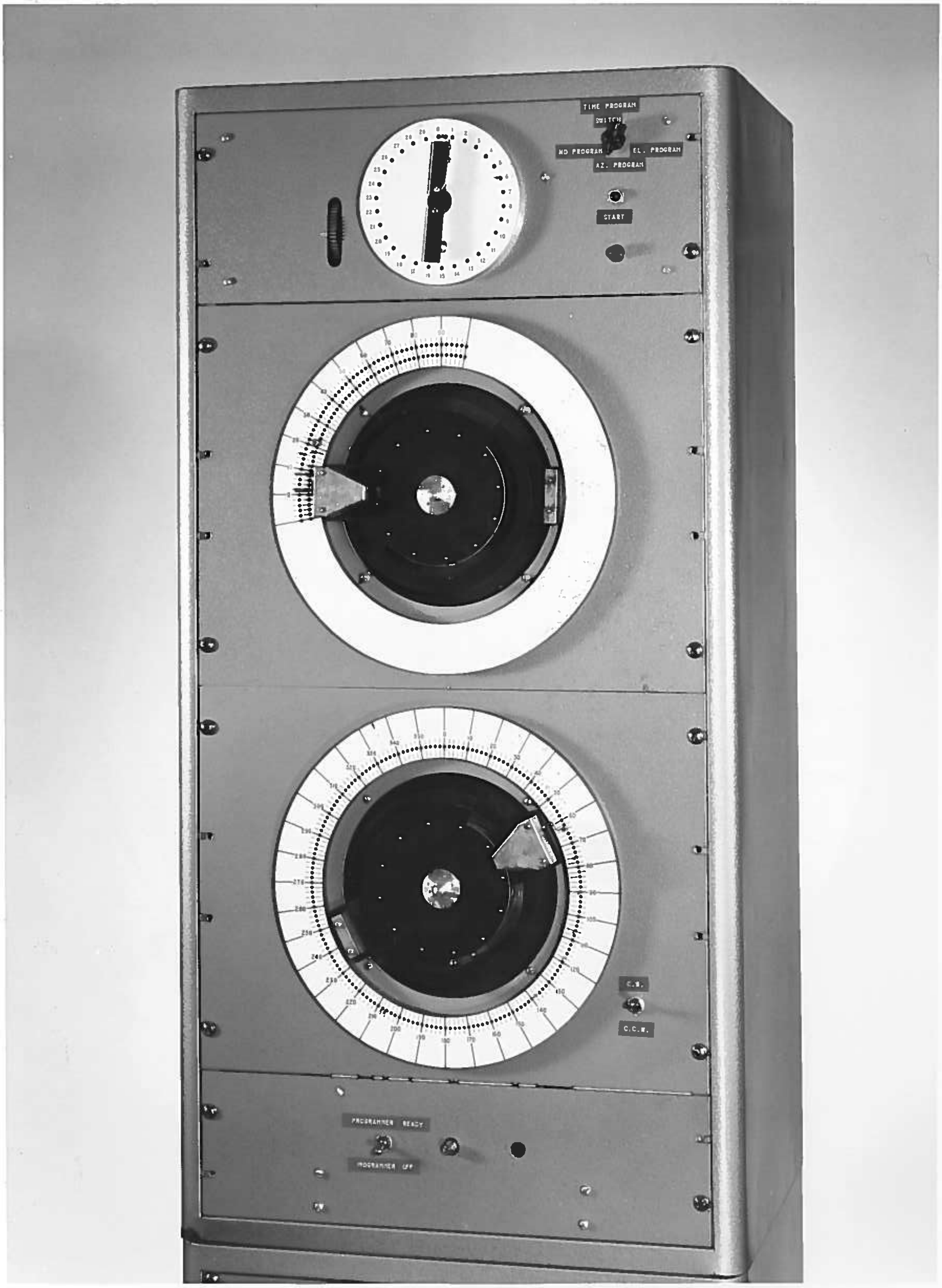

Plate I — Antenna Programmer

(top to bottom) time programmer, elevation circle, azimuth circle

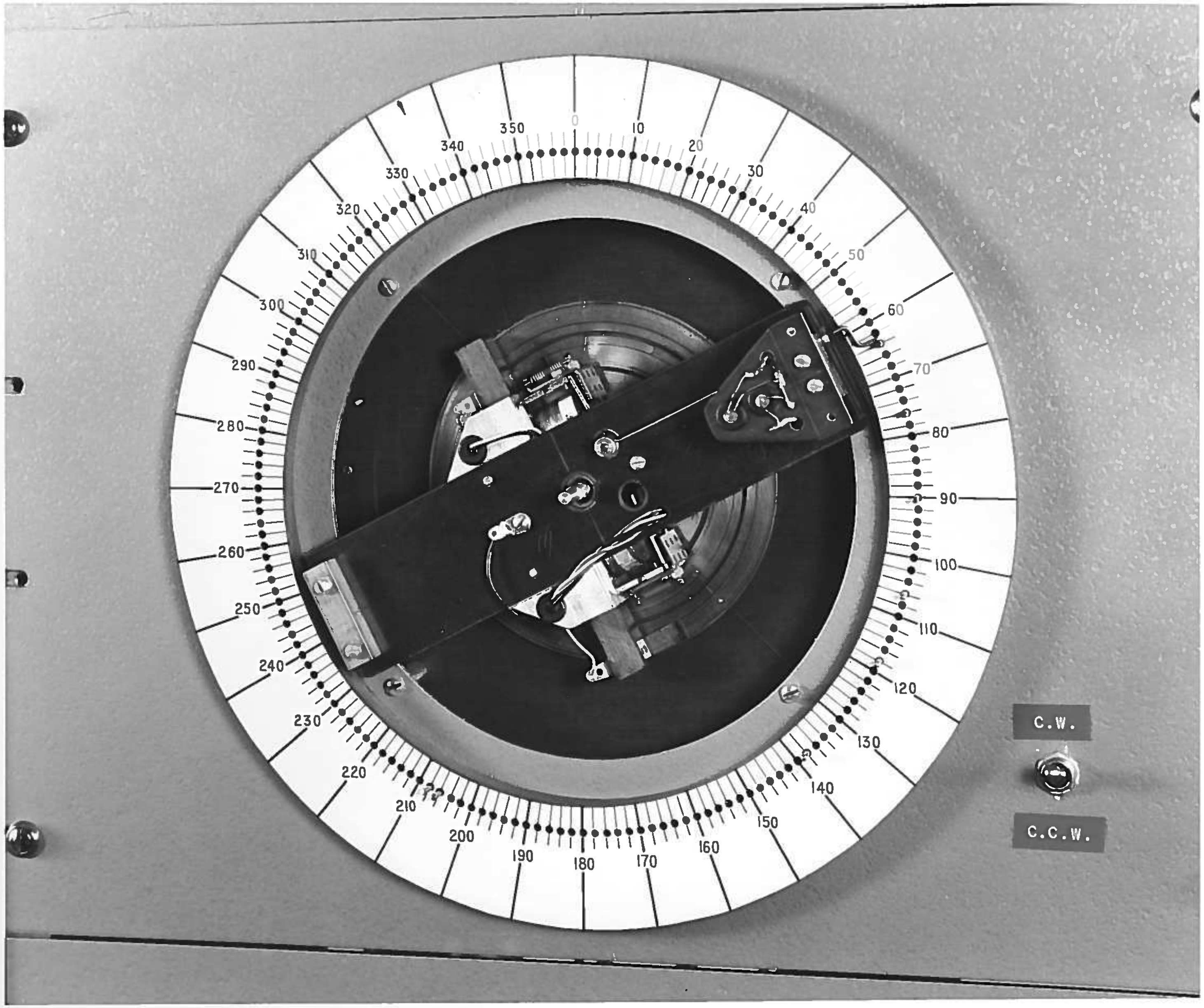

Plate II — Azimuth Programmer (photo-disc and photo-diode cover removed)

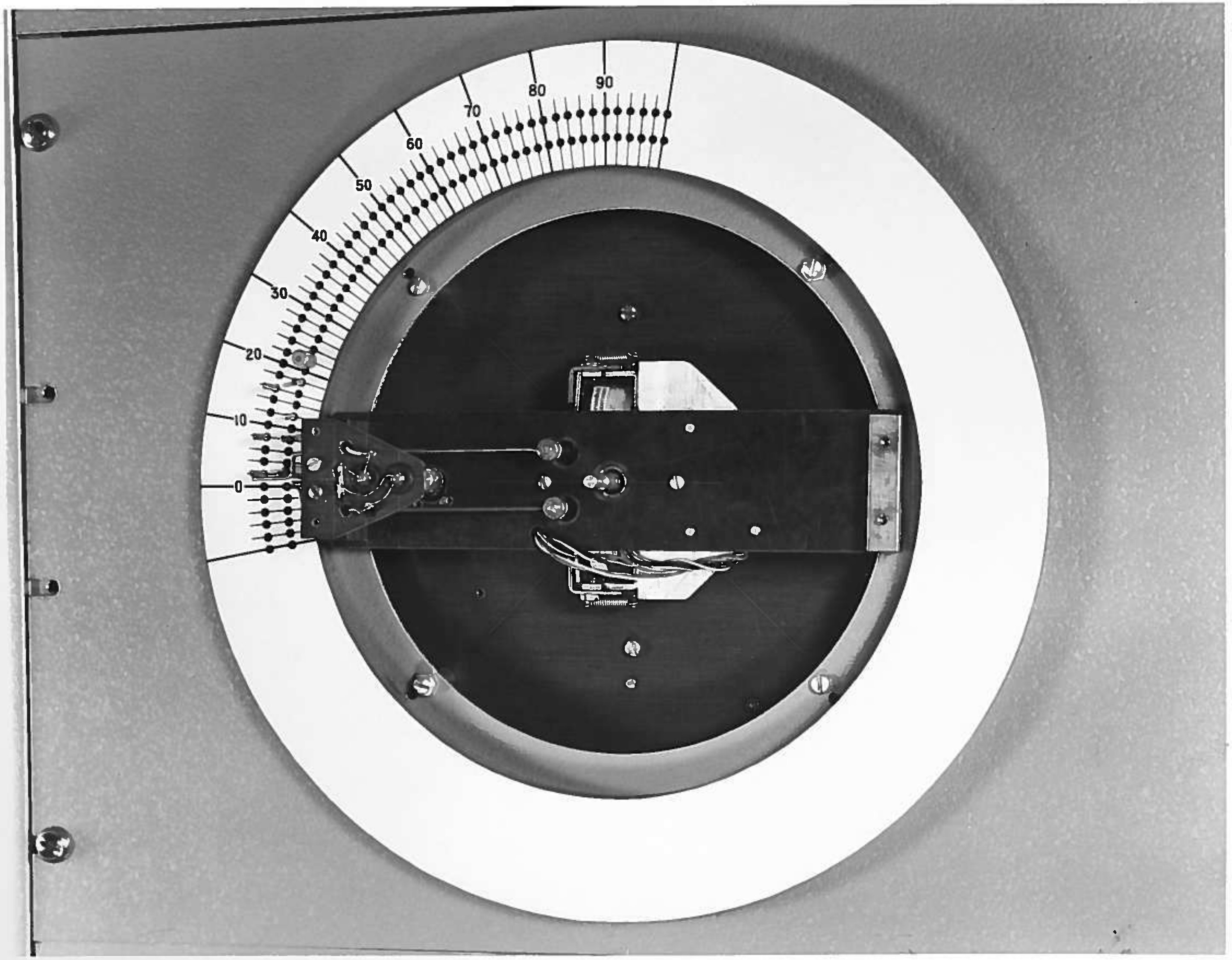

Plate III — Elevation Programmer (photo-disc and photo-diode cover removed)