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Clemence, C.R.

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A SIMPLE ANALOG COMPUTER FOR RADAR SELF-SURVEY

C. R. CLEMENCE

OTTAWA

AUGUST 1966

ABSTRACT

An analog computer for determination of a radar position from the radar ranges and grid coordinates of two known points is described. The computation is based on the simultaneous solution of two right triangles simulated by precision potentiometers in two Wheatstone bridges, the radar position coordinates being generated when the bridge nulls are found as indicated by two centre-zero meters. Root mean square error of about 6 metres in each radar position coordinate is possible at normal radar ranges of 5000 to 9000 metres.

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A SIMPLE ANALOG COMPUTER

FOR RADAR SELF-SURVEY

- C.R. Clemence -

INTRODUCTION

The requirement for an automatic or semi-automatic self-survey device for mobile fire-control radar, such as the AN/MPQ-501, has been stated on a number of occasions. Several computational methods using the facilities already existing in the AN/MPQ-501 radar have been devised, but for various reasons, usually complexity, no particular system has been accepted for use as standard procedure. The need for a simple straightforward device for position determination is apparent. The apparatus described below (Plate I) requires that an operator insert radar ranges and grid coordinates of two known points, and by the simple operation of obtaining nulls on two meters, he may determine the grid coordinates of the radar. The apparatus does not provide azimuth orientation since this would require a relatively high-precision sine-cosine potentiometer or a resolver, such as already exists in the radar, and which can be used in a simple manner to determine the orientation once the radar position is known. However, if so desired, the orientation can be provided quite easily in this apparatus, as explained near the end of this report.

PRINCIPLE OF OPERATION

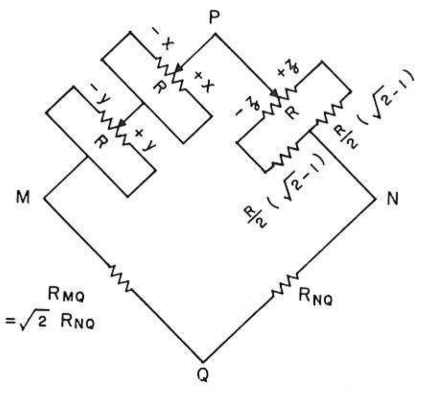

Fig. 1 Arrangement of potentiometers in a Wheatstone bridge

The basic principle of solution of a right triangle by means of a Wheatstone bridge has been known for many years. It consists of connecting linear potentiometers in the arms of the bridge, as shown in Fig. 1 where the resistances between the short-circuited ends and slider of each potentiometer are utilized. In all cases the quantities x, y, or z, which are being simulated, are measured from zeros established by slider positions, which are usually, but not necessarily, at the potentiometer mid-points. For each potentiometer connected in this manner, for $x = 0$ at mid-point, the resistance from slider to short-circuited ends is

$$\frac{\frac{R}{2}(1 - x)\frac{R}{2}(1 + x)}{R} = \frac{R}{4}(1 - x^2). \tag{1}$$

For the bridge circuit of Fig. 1, with sliders at mid-points, we have in the arm PM

$$R_{PM} = \frac{R}{4}(1 - x^2) + \frac{R}{4}(1 - y^2)$$

$$= \frac{R}{4}[2 - (x^2 + y^2)]. \tag{2}$$

And, in the arm, PN, we have

$$R_{PN} = \frac{\frac{R}{2}(\sqrt{2} - z)\frac{R}{2}(\sqrt{2} + z)}{\sqrt{2}\,R}$$

$$= \frac{R}{4\sqrt{2}}(2 - z^2). \tag{3}$$

If the resistances of the other arms are adjusted so that $R_{MQ} = \sqrt{2}\,R_{NQ}$, (4)
then the bridge will balance for a right-triangle solution.

At balance, $$R_{PN} = \frac{R_{NQ}}{R_{MQ}} R_{PM}. \tag{5}$$

From equations (3), (4), and (5)

$$\frac{R}{4\sqrt{2}}(2 - z^2) = \frac{1}{\sqrt{2}}\frac{R}{4}[2 - (x^2 + y^2)], \tag{6}$$

whence $z = \sqrt{x^2 + y^2}$, as required.

If we now let the x and y of Fig. 1 represent the difference easting and northing, respectively, between the radar and a known point and z the radar range to the point, then at bridge balance, one possible combination of these quantities will be generated as a solution of the right triangle.

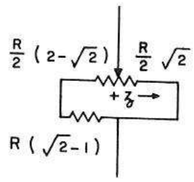

Fig. 2 Zero offset and series resistance as used with range-simulating potentiometer

It is pointed out that the derivation above is directed towards having all of the potentiometers of the same value. Since specified resistances of linear potentiometers can be obtained only by selection, it is desirable that design resistances be equal rather than in some ratio to one another. In addition, the gearing of each to a handwheel and mechanical counter is contemplated so that the mechanical scale factors will be fixed at a predetermined value. The most convenient method of obtaining a resistance, $\sqrt{2}R$, for the z potentiometer has been found to be that of offsetting the slider and using a pre-set resistance, $(\sqrt{2} - 1)R$, as shown in Fig. 2. This is permissible in this application since z will represent a radar range which can have only positive values.

SOLUTION USING TWO BRIDGES

As stated above, it is desired to produce grid coordinates of the radar by using ranges to two known points. If two bridges, A and B, such as that described above, each simulating the relationship of one of the known points to the radar, are constrained so that the same coordinate errors (easting, northing, or both) are maintained in them, the situation may be represented as shown in Fig. 3. The quantities S_A and S_B represent the bridge error voltages when the error in the coordinate position, C, is small relative to radar ranges R_A and R_B, to points A and B, respectively. It is evident that zero error is obtained in both bridges only at one point, and that the combined bridge errors S_A and S_B, can be utilized in determining the corrections to be applied. These may be conveniently termed "radial" and "tangential" errors. If we designate those errors in the directions of C and D as radial, we have for the radial error

$$S_R = (S_A + S_B)/2 \cos \frac{\alpha}{2}, \qquad (7)$$

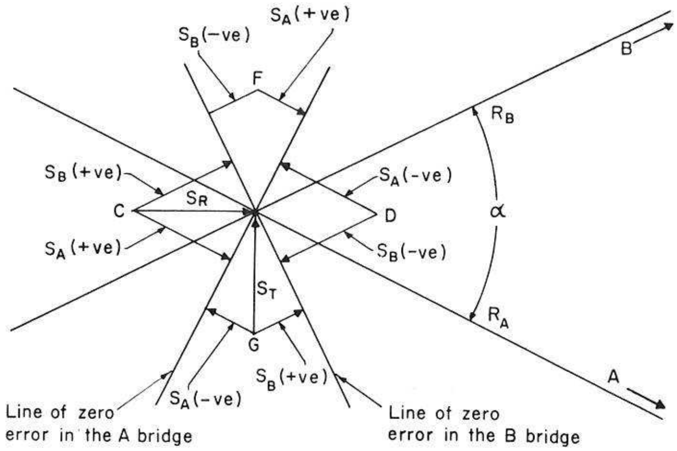

Fig. 3 Graphical relationship of Wheatstone bridge errors

where S_A and S_B are positive in the direction of C and negative in the direction of D, and α is the angle subtended by A and B. Similarly, the combined tangential error in the direction of F or G is

$$S_T = (S_A - S_B)/2 \sin \frac{\alpha}{2} , \tag{8}$$

where S_A and S_B have polarities as described above for S_R. These equations indicate that the angle α should be as close to 90° as possible. However, tests have shown no significant deterioration in the solution at any angle between 45° and 135° and that solutions are possible outside this region.

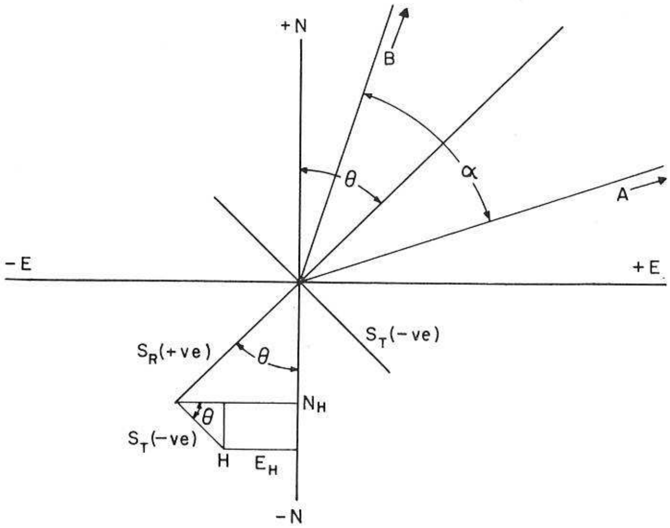

Fig. 4 Vector components of easting and northing corrections

The relationship between S_R, S_T, and the easting and northing error signals is shown in Fig. 4, where the axis has been rotated in such a manner as to show the easting correction, E_H and northing correction, N_H, from any point H.

By inspection it is seen that

$$E_H = S_R \sin\theta + S_T \cos\theta \tag{9}$$

$$N_H = S_R \cos\theta - S_T \sin\theta , \tag{10}$$

and that the relationships hold through any angle providing the points A and B are designated so that A is clockwise with respect to B and the angle θ is measured clockwise from grid north to a line bisecting the angle between A and B at the radar.

The corrected values for easting and northing are obtained when the bridges are nulled; i.e., when S_A and S_B are zero. Simplification of the circuitry by taking

$$S_R = S_A + S_B \tag{11}$$

and

$$S_T = S_A - S_B \tag{12}$$

suggests itself and has been investigated. Some error signal reversal at angles outside the arc 45° - 135° has been noted which, however, does not prevent the correct solution being obtained when the simple operating procedure is followed. S_R and S_T are therefore taken as shown in equations (11) and (12), respectively.

The angle θ is not required to be known accurately but must be estimated and inserted by the operator. In all bench tests, the angle was estimated from a simple sketch of the relative positions of points A, B, and the radar, and no difficulty was encountered at any time.

DESIGN CONSIDERATIONS

Electrical aspects of the design comprise resistance and linearity requirements of the potentiometers. As a design goal the apparatus should accommodate distances between radar position and points A or B up to a maximum of 10,000 metres in either easting or northing. The range to either A or B must be not less than either of the easting or northing intervals. To obtain this on commercially available standard 10-turn potentiometers requires 2000 metres/turn. The best available linearity is about 0.02% (= 4 metres) and about 1% in resistance value.

It can be shown that a 1% resistance error can be reduced by a factor of 8 by means of a shunt resistance, and by adjusting for zero error at mid-range the maximum error in the useful region can be made about 0.03%. In this case, the maximum resistance adjustment was restricted to 0.5% by judicious selection of the potentiometers specified to resistance accuracy of 1% and linearity of 0.02%, so that the over-all potentiometer probable error would not be more than about 5 metres in an easting or northing swing of ±10,000 metres.

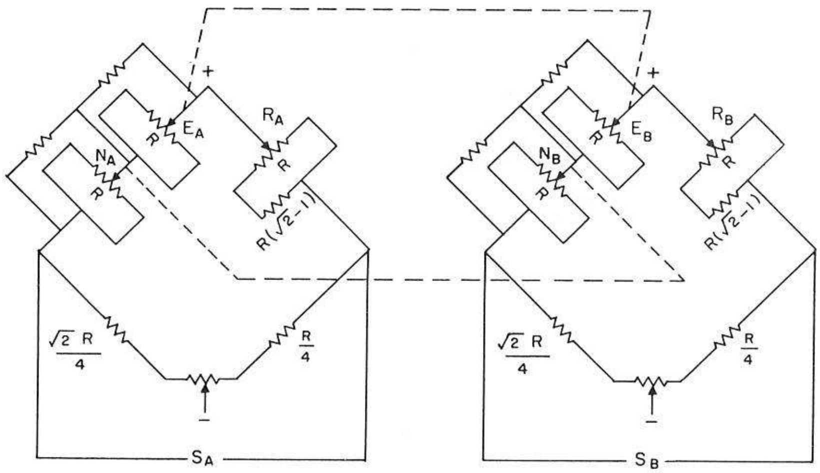

Fig. 5 Wheatstone bridge circuit diagrams
(Dotted lines indicate mechanical connections.)

The complete bridge diagram is shown in Fig. 5. Note the resistors in shunt with the main potentiometers to bring the operating resistances as close as possible to a common value.

Mechanical aspects of the design include backlash considerations and the use of mechanical differentials which, when properly scaled, are virtually error-free in generating easting and northing differentials between positions A and B and the radar. The mechanical schematics for the easting gearing and the northing gearing, which are identical, are shown in Fig. 6. In the gearing it is necessary only to ensure that backlash remains an insignificant quantity and that handwheel rotations make suitable relationships with the counters and potentiometers so that the difference between E_A and E_R is transmitted to the easting potentiometer, and similarly with northing. Actual potentiometer direction of rotation is immaterial since the ends of each are short-circuited.

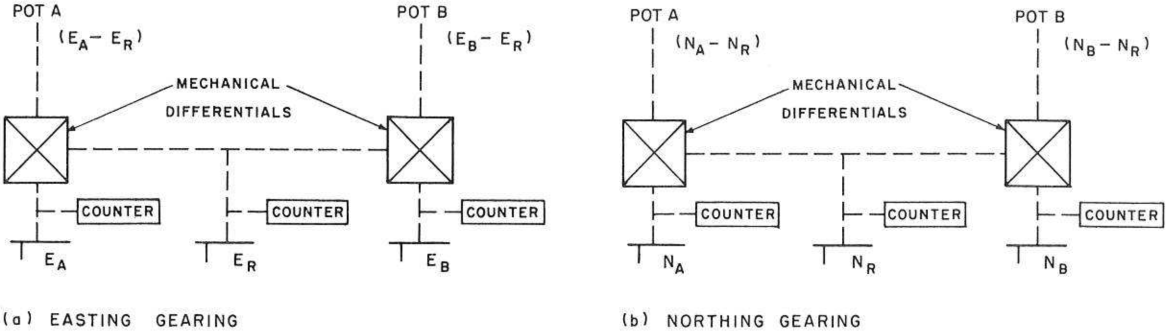

Fig. 6 Mechanical schematics of easting and northing gearing

CIRCUIT DESCRIPTION

The computing circuits are shown in Fig. 7. Separate floating direct voltages are used across each bridge and the error voltages are applied to operational-type amplifiers having d-c response. The first pair of amplifiers A1 and B1 have a controlled gain of 10 and outputs designated as S_A and S_B. Note that the gain-controlling resistances are not critical since the solution is obtained at zero signal in all amplifiers. However, zero offsets and drift will affect the nulls directly, and good quality amplifiers with temperature characteristics appropriate to the expected use are required for A1 and B1. With a gain of 10 in these, the requirements of the other amplifiers, all with unity gain, are much less stringent.

Amplifiers A2 and B2 produce the sum and difference, respectively, of S_A and S_B, with an inverse sum and difference being produced in A3 and B3. The outputs of these four amplifiers are applied to standard quality sine-cosine potentiometers having two sliders at right angles, as shown. These sliders are appropriately connected to A4 and B4 to produce the easting and northing correction equations:

$$E = S_R \sin \theta + S_T \cos \theta$$

$$N = S_R \cos \theta - S_T \sin \theta .$$

These corrections are applied by the E_R and N_R handwheels. When both meters show null, the correct easting and northing of the radar has been found.

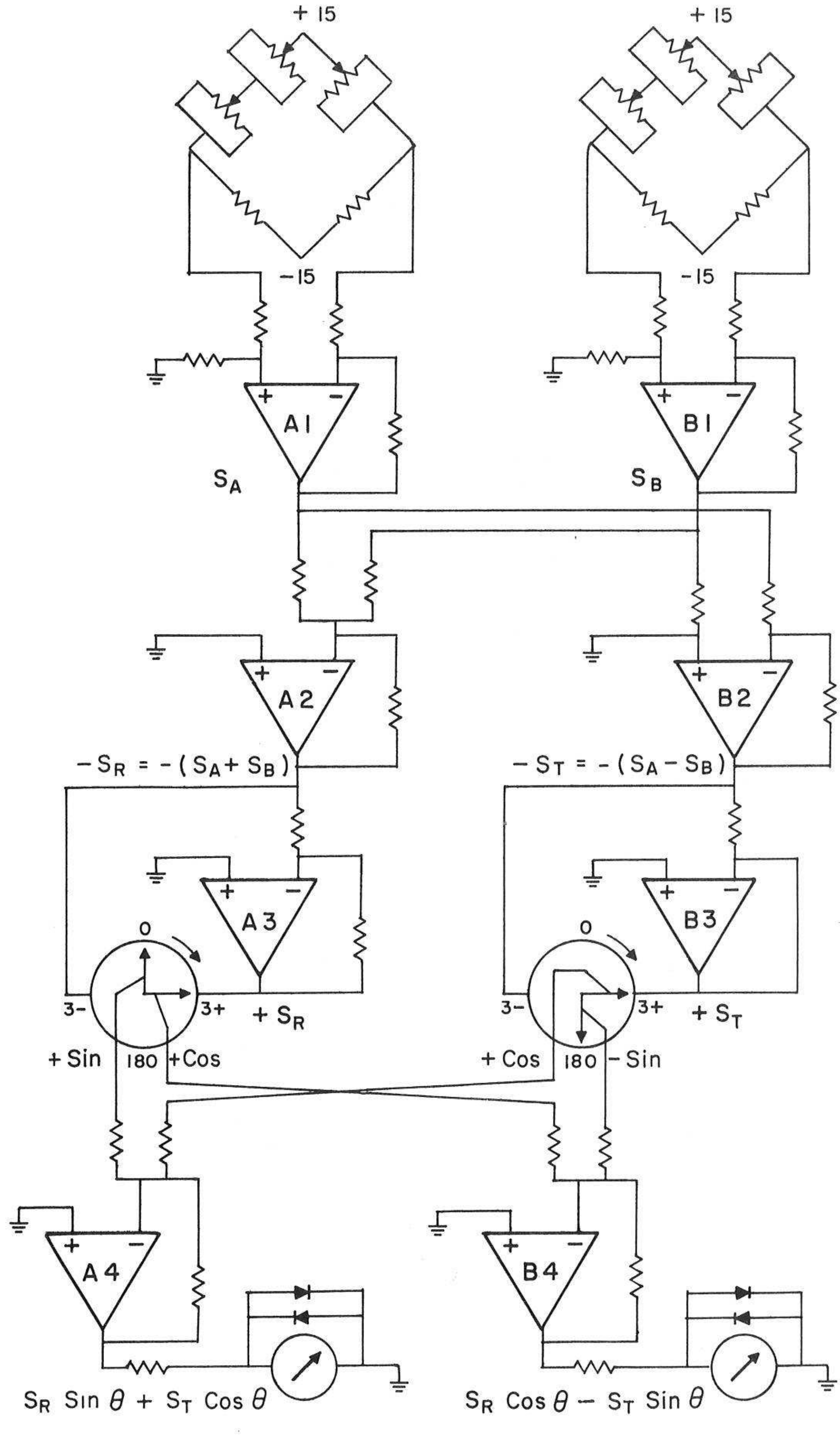

Fig. 7 Computing circuit, showing use of operational amplifiers

TEST RESULTS

A series of problems utilizing ranges to A and B in the region 5000-9000 metres, with angle α between 45° and 135°, has been applied. Root mean square error for all problems was about 6 metres in each of easting and northing. The average solution time which includes the time required to insert the known coordinate data was less than two minutes. Not included, however, is the time required to lay the radar on points A and B and to determine the ranges to these points.

ORIENTATION

As mentioned near the beginning of this report, an orientation azimuth can be determined in the radar AN/MPQ-501. The procedure for doing so may be summarized as follows:

a) Insert radar position coordinates as determined by the self-survey device.

b) Review the positions of points A and B to determine the one making the smallest angle with a north-south line or an east-west line through the radar.

c) Align the radar on the point selected, and set the display marker on the signal from that point.

d) If the point selected is near a north-south line, adjust the orienting knob to obtain correct easting on the target counter. Alternatively, if the point is near the east-west line, adjust the orienting knob to obtain correct northing.

e) Align the radar on the other point and check that easting and northing are correct within ±15 metres.

As also mentioned, the present apparatus may be modified rather simply to produce orientation. It would require that at least one of the sine-cosine potentiometers be relatively precise and would require installation of a suitable multiple-pole switch to obtain the circuit configuration of Fig. 8. In this mode, the E_A, N_A, and R_A (or E_B, N_B, and R_B) potentiometers are removed from the bridges and are placed across the supply voltages. Orientation is found by adjusting the sine-cosine potentiometer until $R_A \sin\theta = E_A$ and $R_A \cos\theta = E_B$, as shown by nulls on the meters at the outputs of A4 and B4. As a general rule, nulls will not be found on both meters simultaneously, in which case nulling of the more sensitive meter should provide the better result. The switching can, of course, be expanded to provide an azimuth to both points, A and B, so that a mean value can be deter-

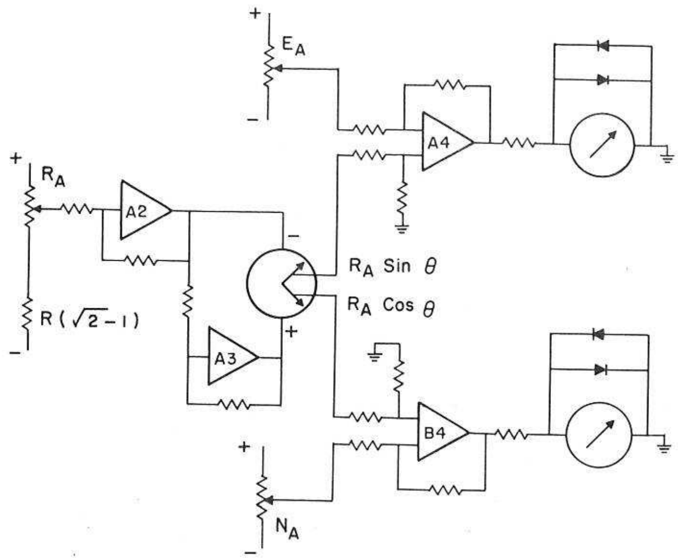

Fig. 8 Circuit configuration to determine orientation

mined by laying the radar on A and B successively and splitting the error between them.

It is estimated that orientation can be determined to a probable error of about 2 mils of angle by either of the above methods. It is suggested that the radar method is preferable because of the precision resolver included in its system.

ACKNOWLEDGMENT

The able assistance of Mr. R. Pritchard who built and tested a breadboard model of the device is hereby acknowledged.

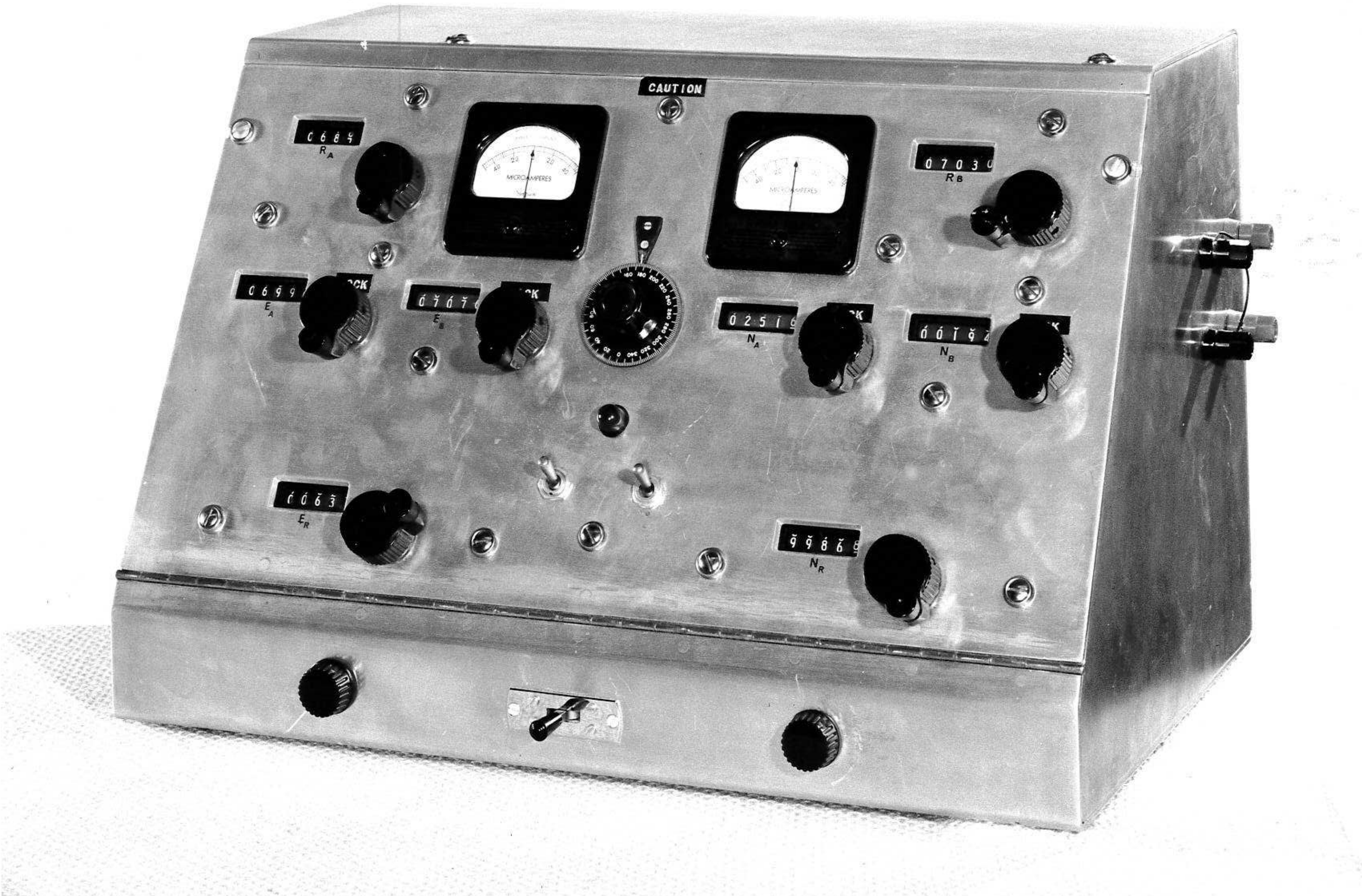

Plate I — A simple analog computer for radar self-survey