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TR-974

A NEW GUIDING AND TRACKING SYSTEM

Henry P. Kalmus

20 September 1961



DIAMOND ORDNANCE FUZE LABORATORIES
ORDNANCE CORPS • DEPARTMENT OF THE ARMY

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Approved by

W. S. Hinman, Jr.
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ABSTRACT

A new application of the near-field theory is described which permits determination of the relative bearing of one object with respect to another by a simple phase measurement without an additional reference signal. The same instrument is used to measure distance between the objects. The angle indication is independent of distance.

1. INTRODUCTION

The guidance method described herein was designed originally to aid vehicles to follow one another. Many situations in which it is desirable to determine the relative bearing and range of one moving object with respect to another should prove amenable to the same technique.

Two measurements have to be performed in the tracking vehicle B: The distance to the leading vehicle A has to be measured; and the angle between the direction of motion of B (its horizontal axis) and its line of sight to A must be determined. This information is sufficient to steer B in such a way that it is always following A, maintaining a distance of, say, 50 ft between A and B. The system can be used either for fully automatic steering of vehicles, or as an aid for the driver during night operation. In the latter case, the information is transmitted to him by sound signals, enabling him to use his visual sense for observing the road itself. At present, usual operation during darkness is based on continuous observation of the tail lights of the leading vehicle. Hence, the driver cannot observe the road simultaneously and is in danger of driving off the road if the leading vehicle suffers an accident of this kind.

The state-of-the-art makes it possible to choose between many systems for the measurement of distance and angle. Electric, magnetic or sonic fields can be employed. For instance, an automatic direction finder can be used in the tracking vehicle whereby some techniques similar to omnidirectional air navigation ranges are employed. The leading vehicle carries a radio transmitter with a V-antenna which produces a horizontally polarized wave essentially constant for all azimuthal angles. The field is received in the tracking vehicle by a mechanically rotating horizontal dipole. The phase of the received signal envelope is compared with the phase of a reference signal which is determined by reference to the axis of B. This way, the angle between the axis of B and the line of sight to A is measured. Or, a near field system may be chosen whereby an omnidirectional field is produced in A and observed in B. This system, for example, can consist of a vertical magnetic dipole in A, fed by a low-frequency source so that B is located always in the near field. Two dipoles are arranged in B, separated by a fixed base line at a right angle to the vehicle axis, and the two induced voltages are compared. The field strength falls off with the third power of the distance, so that the sum and differences of the two

voltages are very sensitive measures for distance and angle respectively (triangulation). If this method is employed, the angle indication is distance dependent. For the first method, the angle measurement is independent of distance, but mechanically rotating parts are required. In addition, the distance measurement becomes more cumbersome.

2. NEW SYSTEM

The new method is cooperative and based on an application of the near-field theory. A feature of quasi-stationary fields, however, is employed which is not well known and which permits derivation of the angle independent of distance by a simple phase measurement without the help of an additional reference signal and without rotating parts. Before describing the details of the method, an important feature of the quasi-stationary field that does not exist in the radiation field should be pointed out.

In figure 1, A is a dipole that is short compared with the wavelength so that the current is uniform over its length. B is a receiving dipole that can be lined up either with r , or normal to r , so that the field strength E_r and E_θ can be measured.^{1/}

For:

$$K = \omega \sqrt{\mu \epsilon} = \frac{2\pi}{\lambda} \quad \text{and} \quad \eta = \sqrt{\frac{\mu}{\epsilon}} \doteq 120 \pi \text{ ohms},$$

$$E_r = \frac{I_o h}{4\pi} e^{-jk r} \left[\frac{2\eta}{r^2} + \frac{2}{j\omega \epsilon r^3} \right] \cos \theta \quad (1)$$

$$E_\theta = \frac{I_o h}{4\pi} e^{-jk r} \left[\frac{j\omega \mu}{r} + \frac{1}{j\omega \epsilon r^3} + \frac{\eta}{r^2} \right] \sin \theta \quad (2)$$

Consideration must be given only to $1/r$ and $1/r^3$ terms for the radiation field and near field, respectively, so that eq (1) and (2) can be rewritten:

$$E_r^{\text{rad.}} = \quad (3)$$

$$E_\theta^{\text{rad.}} = \frac{M}{r} \sin \theta \quad (4)$$

and

$$E_r^{\text{near}} = \frac{2N}{r^3} \cos \theta \quad (5)$$

$$E_\theta^{\text{near}} = \frac{N}{r^3} \sin \theta \quad (6)$$

^{1/}Fields and Waves in Modern Radio, Ramo and Whinnery, 2nd Edition, (1953) p 498.

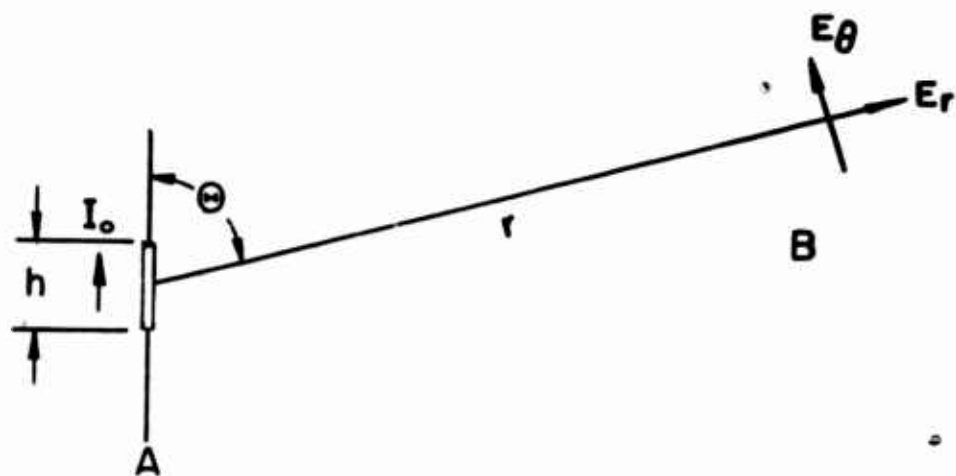


Figure 1. Field produced by short dipole.

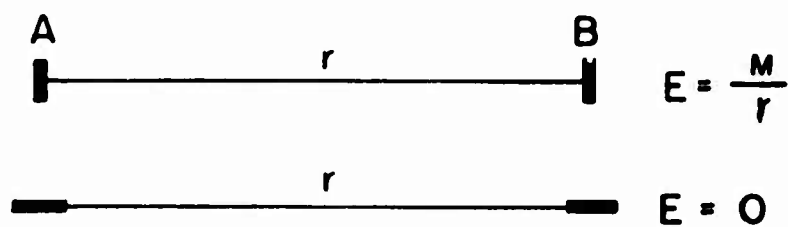


Figure 2. Diagram showing received voltages for in-line and paralleled dipoles A and B in a far-field range.

M and N are constants, depending on I_0 , h, k, and η .

Equations (3) and (4) express the well known fact that no E_r exists in the radiation field. As shown in figure 2, for dipoles A and B parallel and $\theta = \pi/2$, the highest possible voltage will be received. For both dipoles in line, the voltage is zero.

Using the near field, however, equations (5) and (6) show that the received voltage for the two dipoles in line has now the highest possible value. The voltage is twice as high as that for the dipoles parallel and $\theta = \pi/2$. This condition is shown in figure 3.

Because of the symmetry between electric and magnetic fields, equations 3 to 6 can simply be applied to magnetic instead of electric dipoles.

In the new guiding system, a circularly polarized field is produced in A. The transmitter consists of two solenoids with horizontal axes which are arranged at right angles to each other. They are fed from a low-frequency source in phase quadrature. In other words, two magnetic dipoles in space and phase quadrature produce a rotating magnetic field. The receiver in B again contains two coils in space quadrature, measuring the field strengths E_1 and E_2 . The wavelength is long compared with r, so that the near field conditions apply. The receiver dipoles are tilted horizontally by the angle α with respect to the line of sight between A and B. It will be shown that α can be determined by measuring the phase difference $\Delta\varphi$ between the phase angles φ_1 of E_1 and φ_2 of E_2 . Because a rotating field is produced by A and because we are interested only in the relative phase shift between E_1 and E_2 , we can perform the computation without loss of generality by assuming the transmitter dipoles always respectively in line and normal to the line of sight between A and B. The angle θ in figure 1 becomes, therefore, zero and $\pi/2$ respectively.

As shown in figure 4 and considering equations (5) and (6), dipole A produces field $E_r = 2N/r^3$ and $E_\theta = 0$. Dipole A_2 produces an $E_\theta = jN/r^3$ and an $E_r = 0$. Because of the tilt, voltages from A_1 and A_2 will be induced in each of the receiving dipoles and we may write for $E = N/r^3$:

$$E_1 = E (2 \cos \alpha + j \sin \alpha) \quad (7)$$

$$E_2 = E \left[2 \cos \left(\alpha + \frac{\pi}{2} \right) + j \sin \left(\alpha + \frac{\pi}{2} \right) \right]$$

$$E_2 = E (-2 \sin \alpha + j \cos \alpha) \quad (8)$$

$$\tan \varphi_1 = \frac{2 \sin \alpha}{\cos \alpha} = 2 \tan \alpha$$

$$\tan \varphi_2 = - \frac{\cos \alpha}{2 \sin \alpha} = - \frac{1}{2 \tan \alpha}$$

$$\Delta\varphi = \tan^{-1} \left(\frac{1}{2} \tan \alpha \right) - \tan^{-1} \left(- \frac{1}{2 \tan \alpha} \right)$$

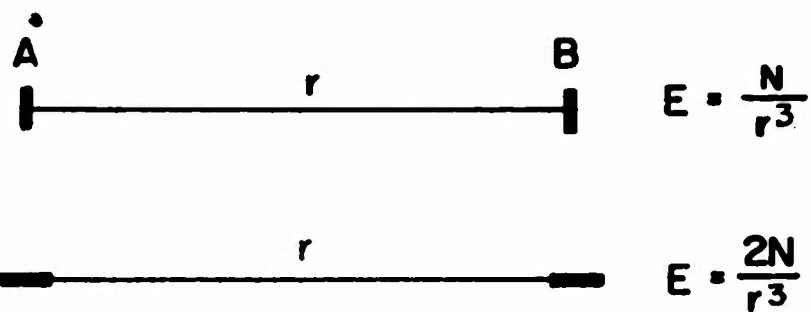


Figure 3. Diagram showing received voltages for in-line and paralleled dipoles A and B in a near-field range.

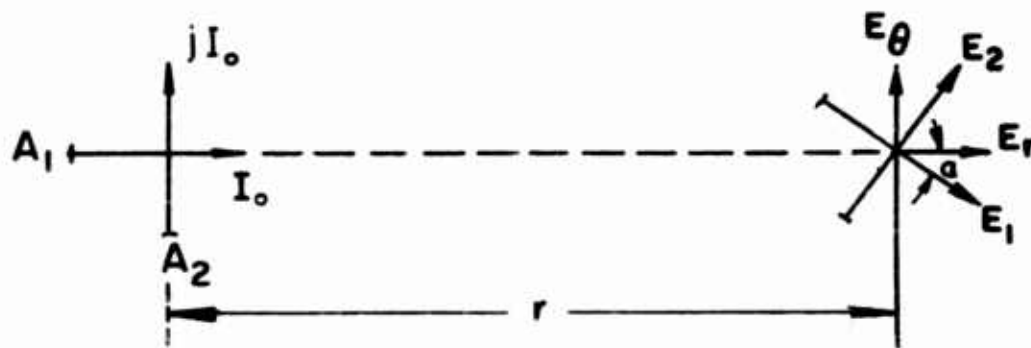


Figure 4. Diagram showing dipole configuration for the new system.

Using the relation:

$$\tan^{-1} x - \tan^{-1} y = \tan^{-1} \frac{x - y}{1 + xy} ,$$

$$\Delta\varphi = \tan^{-1} \frac{\frac{1}{2} \tan \alpha + \frac{1}{2 \tan \alpha}}{1 - \frac{1}{4}}$$

$$\Delta\varphi = \tan^{-1} \left[\frac{2}{3} \left(\frac{\sin \alpha}{\cos \alpha} + \frac{\cos \alpha}{\sin \alpha} \right) \right] = \tan^{-1} \left(\frac{2}{3} \frac{1}{\sin \alpha \cos \alpha} \right)$$

$$\Delta\varphi = \tan^{-1} \frac{4}{3 \sin 2\alpha}$$

For:

$$\alpha = 0, \Delta\varphi = 90^\circ$$

$$\alpha = 45^\circ, \Delta\varphi = 53^\circ 10'$$

$$\alpha = -45^\circ, \Delta\varphi = 126^\circ 50'$$

In figure 5, the phase difference $\Delta\varphi$ is plotted versus α ; it can be seen that for $\alpha = +90$ deg, $\Delta\varphi$ is 90 deg. Hence, nonambiguous direction indication can be obtained as long as the rotation does not exceed 90 deg.

To judge the sensitivity of the system, the slope of the $\Delta\varphi$ wave will be computed so that the phase shift for, say, 1 deg rotation of the receiver can be determined.

Using the relation:

$$\frac{d \tan^{-1} x}{dx} = \frac{1}{1 + x^2} , x = \frac{4}{3 \sin 2\alpha}$$

$$\frac{d(\Delta\varphi)}{d\alpha} = \frac{24 \cos 2\alpha}{9 \sin^2 2\alpha + 16}$$

for

$$\alpha = 0, \frac{d(\Delta\varphi)}{d\alpha} = -\frac{3}{2}$$

$$\Delta\varphi = \frac{d(\Delta\varphi)}{d\alpha} \Delta\alpha$$

for

$$\Delta\alpha = 1^\circ, \text{ we obtain } \Delta\varphi = -1.5^\circ.$$

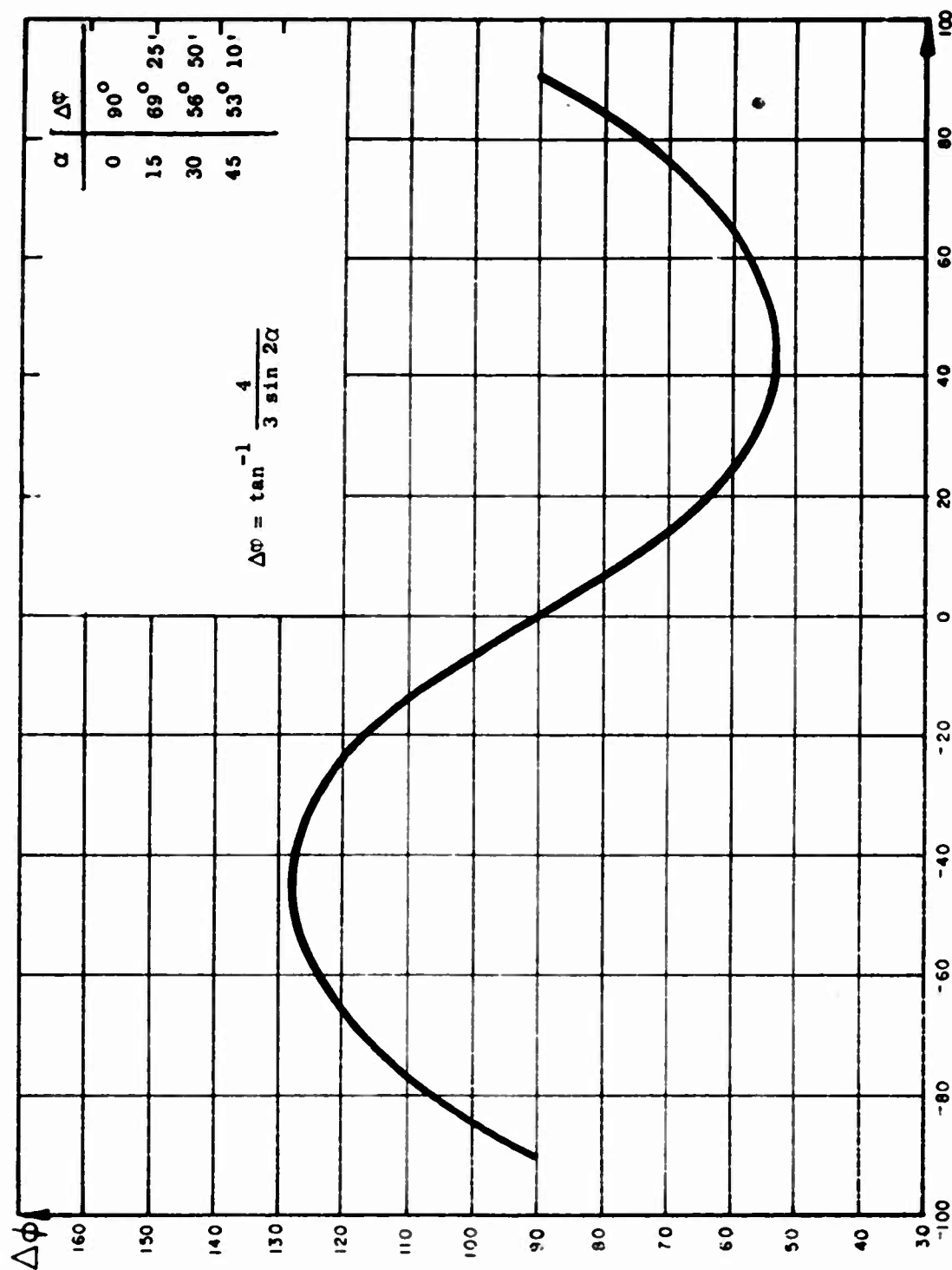


Figure 5. Phase difference $\Delta\phi$ versus α .

This is a value measurable, even with a simple phase meter, so that small direction changes can be determined with high accuracy.

The appearance of the curve in figure 5 suggests a simple harmonic function. Indeed, if the function yielding $\Delta\varphi$ is developed in a Taylor series, the first two terms are found to be $\pi/2 - 3/4 \sin 2\alpha$ (see app). This is actually an excellent approximation for all values of α in the range from $-\pi/2$ to $+\pi/2$ as may be found by differentiation of the expression for the difference. The maximum errors occur at $\alpha = -\pi/4$ and $\alpha = +\pi/4$ and are of the order of 6 deg.

As mentioned before, the distance measurement is based on the third power law controlling the quasi-stationary field. It will now be shown that it is only necessary to amplify the voltages induced in the two receiving dipoles, rectify these voltages in a square law device, and add the d-c potentials.

Rewriting equations (7) and (8), we obtain

$$E_1 = \frac{N}{r^3} (2 \cos \alpha + j \sin \alpha)$$

$$E_2 = \frac{N}{r^3} (-2 \sin \alpha + j \cos \alpha)$$

After amplification, the voltages have the absolute magnitudes

$$|E_1| = \frac{KN}{r^3} \sqrt{3 \cos^2 \alpha + 1}$$

$$|E_2| = \frac{KN}{r^3} \sqrt{3 \sin^2 \alpha + 1}$$

After rectification, we obtain

$$|E_1|^2 = \frac{K^2 N^2}{r^6} (3 \cos^2 \alpha + 1)$$

$$|E_2|^2 = \frac{K^2 N^2}{r^6} (3 \sin^2 \alpha + 1)$$

Hence,

$$|E_1|^2 + |E_2|^2 = 5 \frac{K^2 N^2}{r^6}$$

The distance indication is independent of the angle α .

It will now be shown that the squaring operation is not critical even if linear rectifiers are employed; there is only a very small angle dependence and the sum of the rectifier outputs can still be used for distance indications.

$$|E_1| + |E_2| = \frac{KN}{r^3} (\sqrt{3 \cos^2 \alpha + 1} + \sqrt{3 \sin^2 \alpha + 1})$$

for $\alpha = 0$:

$$|E_1| + |E_2| = 3 \frac{KN}{r^3};$$

for $\alpha = \frac{\pi}{2}$:

$$|E_1| + |E_2| = 3 \frac{KN}{r^3}.$$

Hence, there is no angle dependence for $\alpha = 0$ and $\alpha = \frac{\pi}{2}$. In between, an error exists which reaches a maximum for $\alpha = \frac{\pi}{4}$. (This can be proved easily by differentiating $\sqrt{3 \cos^2 \alpha + 1} + \sqrt{3 \sin^2 \alpha + 1}$ and letting the differential quotient be zero.)

For $\alpha = \frac{\pi}{4}$:

$$|E_1| + |E_2| = \frac{KN}{r^3} \sqrt{\frac{3}{2} + 1} = 3.16 \frac{KN}{r^3}.$$

Therefore, a maximum error of only 16 percent exists if linear detector is employed. This error occurs only for a bearing angle α of 45 deg; it disappears for $\alpha = 0$ and $\alpha = 90$ deg. The square law device is therefore not critical, and sufficiently accurate distance information can be obtained by deriving $|E_1|$ and $|E_2|$ directly from the limiters or from the AGC circuits.

Fig. 6 is a block diagram of the new system. The transmitter part consists of generator G (for instance a transistor, feeding 2 w power into two coils in space and time quadrature). The receiver contains two similar coils, connected to amplifiers A_1 and A_2 . The amplifiers are equipped with limiters so that symmetric clipping of the signals is obtained over the total amplitude range of the receiver signals. This way, the phases of the simplified signals become independent of amplifier gain and distance so that a correct angle measurement is possible without any critical adjustments. The two signal waves are fed into phase meter P_H , and the phase difference is measured by M_P . The amplifiers furnish two d-c potentials P_1 and P_2 , proportional to the square of the signal amplitudes. These potentials are derived either from the AGC circuit or from the limiter currents directly. A simple resistive network R is used to derive the arithmetic mean between P_1 and P_2 which is measured by meter M_D . Hence, M_D measures distance as explained before.

Because of the fields produced by the ignition systems and the generators in the vehicles, a frequency of 100-kc was chosen. It was found that no noise-suppressing means is necessary if the maximum separation between the vehicles is smaller than 200 ft. Figure 7 shows the two transmitter and two receiver coils. The coils are 6 in. long and have a diameter of 1/2 in. Ferrite cores are employed to increase

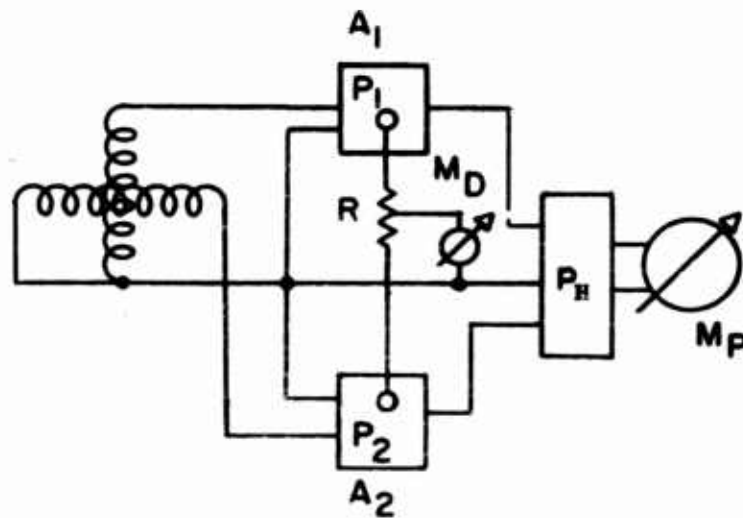
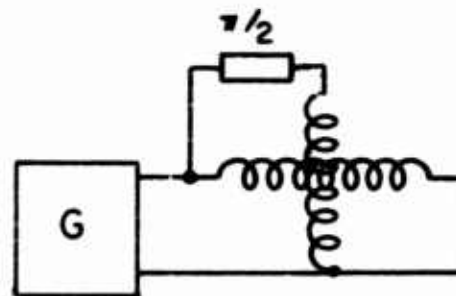


Figure 6. Block diagram of new system.

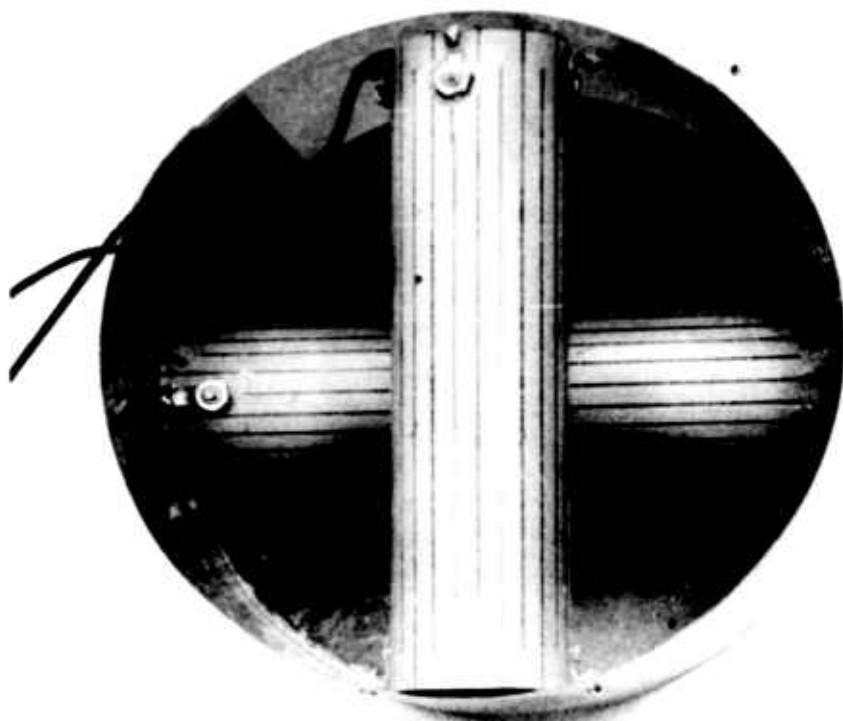


Figure 7. Transmitter and receiver coils.

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the antenna efficiency. The receiver coils are statically shielded. The Q of the coils is 400 so that an a-c power of only 2 w is sufficient to produce the required field. The received voltage depends on the chosen LC ratio and is in the order of 1 mv for a parallel capacity of 1500 μf and a distance of 100 ft.

Because of the high-input voltage, no excessive amplification is required. Limiters, however, have to be carefully designed to avoid nonsymmetric clipping. (Because such amplifiers and phase detectors constitute a well known art, circuit diagrams are not presented in this paper.) The low-carrier frequency makes it possible to transistorize transmitter and receiver at low cost.

3. CONCLUSION

It should be mentioned that the new method can be used whenever a moving object has to be aimed at a target. Guiding boats into narrow locks or refueling airplanes in space are typical examples for the application of the quasistationary field employing a phase detector for the angle measurements.

APPENDIX

Taylor Series for $\Delta\varphi = \tan^{-1} \frac{4}{3 \sin 2\alpha}$.

$$f(x) = f(0) + f'(0) \frac{x}{1!} + f''(0) \frac{x^2}{2!} + f'''(0) \frac{x^3}{3!} + \dots$$

$$f(x) = \tan^{-1} \frac{1}{x} .$$

$$f'(x) = - (1 + x^2)^{-1}$$

$$f''(x) = 2x (1 + x^2)^{-2}$$

$$f'''(x) = -8x^2 (1 + x^2)^{-3} + 2(1 + x^2)^{-2}$$

$$f(0) = \frac{\pi}{2}, \quad f'(0) = -1, \quad f''(0) = 0, \quad f'''(0) = 2.$$

$$x = \frac{3}{4} \sin 2\alpha$$

$$\Delta\varphi = \frac{\pi}{2} - \frac{3}{4} \sin 2\alpha + \frac{9}{64} \sin^3 2\alpha - \dots$$

$$\Delta\varphi \doteq \frac{\pi}{2} - \frac{3}{4} \sin 2\alpha$$

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2. Guidance and tracking system--
Theoretical analysis
3. Phase detection--
Theory
Applications
4. Navigation method--
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3. Phase detection--
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4. Navigation method--
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