# SOME RECENT DEVELOPMENTS IN RADIO-CONTROLLED FLIGHT AND LANDING

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### SUMMARY

This report surveys the present technical status of radio-controlled flight and landing, and discusses some of the recent advances The need for reliable methods of performance testing is pointed out

The problem of extending automatic approach to touchdown is described, with particular reference to the work being done on the null-reference flared glide slope projector at the Technical Development and Evaluation Center, at Indianapolis, Indiana

Some considerations of control methods to be employed in radio-controlled flight on omnirange and computer course lines are presented


### RECENT PROGRESS IN AUTOMATIC APPROACH EQUIPMENT

During the past four years, commercial development of automatic approach has progressed to a point where all major manufacturers of automatic pilots for aircraft now furnish, for use with their respective automatic pilots, an accessory device which couples the ILS crosspointer signals to the automatic pilot This accessory device is known by various names, however, for the purposes of this report it will be called the automatic approach coupler

The purpose of an automatic approach coupler is, on the basis of the ILS signals from the localizer and glide slope receivers in the aircraft, to provide suitable turn and pitch signals to the automatic pilot which will cause the aircraft to be guided accurately down the proper runway approach path The system is ordinarily expected to function down to a low altitude of the order of 50 or 75 feet, at which point the pilot can take over visually and complete the landing manually

While the automatic approach couplers of various manufacturers all have the same basic purpose, they utilize different techniques to accomplish their objective The Technical Development and Evaluation Center now has, installed in its airplanes, automatic pilots with associated approach couplers of three manufacturers A fourth will soon be available Engineers of the Center are in the process of obtaining, through routine flying and special flights for the purpose, practical experience with each type of equipment It will thus be possible at a future time to determine the relative merits of the various different techniques in use

To provide satisfactory approaches, the control system (comprising the radio, approach coupler, autopilot and aircraft) must have stability at all times during actual use This means that, if at any point in the approach the aircraft is displaced from the ILS course or glide slope, the system will initiate an immediate correction to remove the error, and the oscillations which follow, if any, will be rapidly damped

Means for obtaining stabilization in the localizer axis have included the use of a rate signal obtained by differentiating the localizer deviation voltage, a heading signal obtained from a directional gyro, and combinations of both Earliest forms of approach couplers used directional gyro signals alone for stabilization [1] This method suffered the drawback that cross-winds requiring an appreciable crab angle to stay on the course line caused a residual displacement error. The addition of the cross-wind corrector, which was a low speed integrating device, removed the residual error, but it still was necessary to set in the approximate runway heading as a reference for the directional gyro With the advent of the rate method,[2] it was possible, with proper low-pass filtering of the radio signals plus suitable choice of the rate constant, to obtain automatic approaches that had good smoothness, accuracy, and stability even in the presence of variable cross-winds Subsequent development by manufacturers has uncovered

[1] F L Moseley and C B Watts, Jr , "Automatic Radio Flight Control," Proceedings of the National Electronics Conference, October 1946

[2] See footnote 1

other methods of deriving the stabilizing signals The Sperry Gyroscope Company has used a servo-driven speed generator to produce a signal which is proportional to the rate of change of the localizer deviation signal [3] The Eclipse-Pioneer Division, Bendix Aviation Corporation has used a combination of directional gyro signal and rate signal derived with thermal time lag tubes to obtain stabilization [4]

One of the problems which has always plagued designers of automatic approach couplers has been the conversion of the low level dc deviation signals available from the receiver crosspointer circuits to ac which can be amplified in the coupler The problem is made difficult by the requirement that the conversion device have a high order of zero-center accuracy which is unaffected by the passage of time and the subjection of the equipment to operating conditions Any zero-center error in the initial conversion device will result in a corresponding residual displacement error in following the course line Conversion devices which have found use in numerous couplers include copper oxide ring modulators, vibrators, and saturable reactor bridges Each device has its own peculiar limitations A conversion device currently being investigated regarding its applicability to this problem is the Microsen Balance manufactured by Manning, Maxwell, and Moore, Inc This is essentially a specially designed galvanometer of limited movement, the movements of the vane being detected by electrical pick-off means which utilize variations in inductance or capacitance to produce a corresponding ac The spring stiffness constant associated with the galvanometer is vanishingly small, and the device will move from stop to stop with a current of less than one microampere When used in a properly designed circuit employing negative feedback, the device appears to perform the desired function of dc/ac conversion with a permanently high order of zero-center accuracy By virtue of the negative feedback, the gain stability also is high [5]

The problem of obtaining stabilization of the approach path in the glide slope axis has not been as troublesome as in the localizer axis Stabilization is commonly obtained from the pitch attitude signal of a vertical gyro This method is broadly analagous to the use of the directional gyro for stabilization in the localizer axis, and has similar faults, but to a much less obvious extent If the reference pitch angle is incorrectly chosen, there will be a residual error above or below the glide slope, which will remain uncorrected Even if the reference pitch angle is initially correct, but there is a change in along-course component of wind during the descent, or if the fore-and-aft trim of the airplane is changed for some reason, then there also will be a residual error above or below the glide slope This annoying characteristic can be removed in either one of two fundamental ways, just as in the case of the localizer axis control The residual error may be cancelled by a slow speed integrating device, or, the pitch gyro signal may be abandoned as a means of path stabilization, and the stabilization signal may be obtained by measuring the rate of change of glide slope displacement signal Either method produces satisfactory results The latter method was tested experimentally about two years ago at the Technical Development and Evaluation Center, using a modified Minneapolis-Honeywell coupler The results of the investigation were summarized in a paper presented to the Radio Technical Commission for Aeronautics, Special Committee 18, on Automatic Flight Control The contents of this paper are attached to this report as Appendix I The use of the slow speed integrator for removing the residual error now is being investigated in connection with the Sperry coupler A block diagram of this modification is shown in Fig 1 The tests thus far indicate that satisfactory results also can be obtained by this method

[3] P Halpert, "The A-12 Gyropilot," SAE Preprint, Presented before the Society of Automotive Engineers Meeting April 13-15, 1948, New York City

[4] P A Noxon, "Flight Path Control," Aeronautical Engineering Review, August 1948

[5] C G Roper and J F Engelberger, "Electromechanical D-C Amplifier," Electronics, November 1947

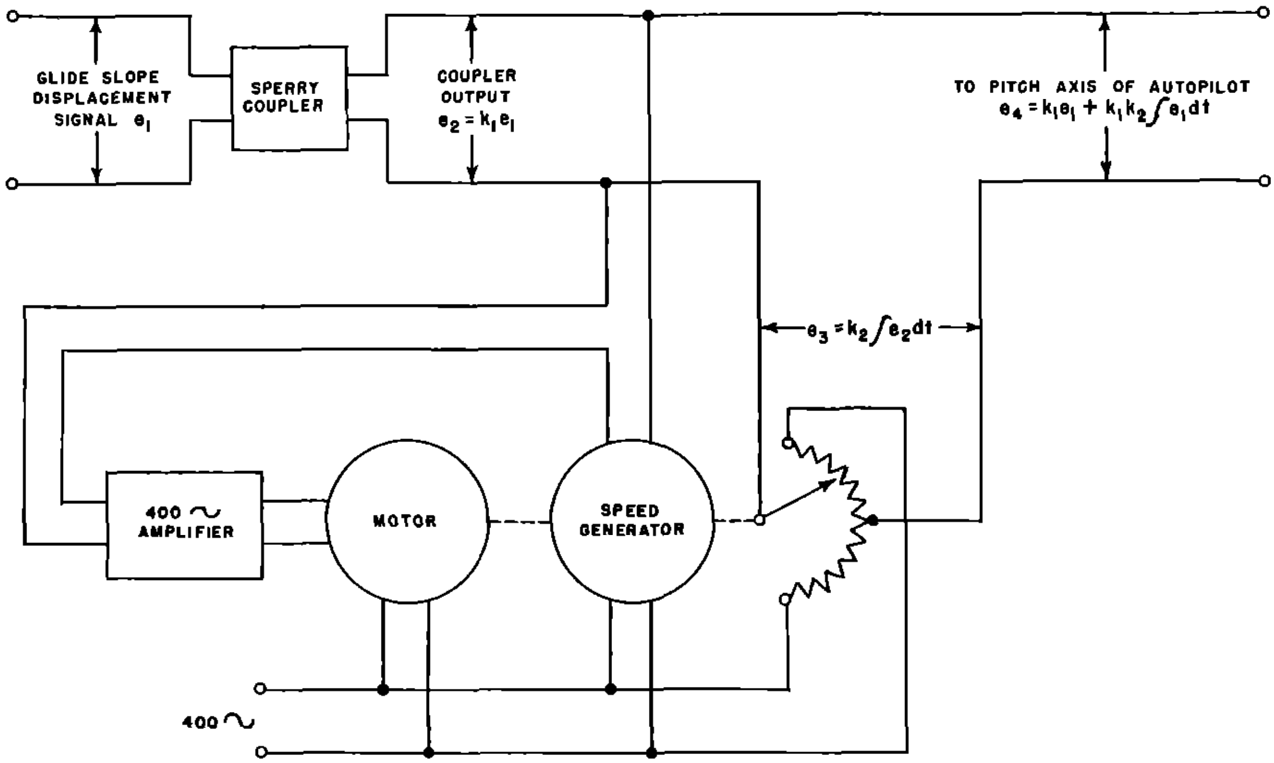



Fig 1 Block Diagram of Integrator Modification for Removal of Residual Displacement Error

On the question of throttle control applied to automatic approach, there has been considerable disagreement among engineers in the field Some feel that throttles should be servoed to hold airspeed or angle of attack constant, others feel that throttle position should be servoed to the glide slope signal, and still others believe that automatic throttle control itself is a useless frill Aircraft installations following each of these philosophies have been made, and it probably will be a matter for operational experience to determine finally the relative merits of each

## METHODS OF INVESTIGATING THE PERFORMANCE OF AUTOMATIC APPROACH EQUIPMENT

While it is true that the ultimate measure of performance of an automatic approach equipment should be based on actual results in flying automatic approaches, nevertheless one or even several test approaches do not furnish a very accurate guide to the performance This is because the wind variations and other transient-producing conditions normally encountered are never quite the same for different approaches, yet it is the response of the system to these random transient effects which determines whether the equipment is performing well or poorly It is well known that if the air is extremely smooth and the wind velocity is constant, then even a poorly operating equipment can present the appearance of providing excellent automatic approaches The system needs rather to be subjected to known disturbances, and the resulting response observed as a measure of performance

Thus, if automatic approach is to come into general operational use, it is quite important that standard test procedures for determining the performance of the equipment be devised

In general the automatic approach coupler is a transfer device having two channels, each channel having an input and an output The two inputs receive the crosspointer deviation signals and the two outputs, feeding to the autopilot proper, produce turn and pitch changes If in each channel the output can be specified as a function of the input, then the performance of the coupler is completely defined The specification of the ac steady state transfer function is somewhat complicated by the fact that some form of limiting is invariably included as an important characteristic of the device. However, for an investigation of stability, it is ordinarily sufficient to consider only the transfer function at low levels, where the coupler usually behaves as a substantially linear device It is fortunate that this is the case, since stability about the course line is undoubtedly the most important single attribute of a high performance automatic approach control system

To obtain the low level transfer function of a coupler, a steady sinusoidal ac signal is applied to the input, and the vector ratio of output to input signals is observed Then, as the frequency of the input signal is varied through the spectrum of interest, the amplitude and phase of the transfer function may be plotted The frequency spectrum of interest in couplers normally extends from about 0 001 cps to about 10 cps It is important in making these measurements of transfer function to allow enough time, at each frequency, for a true steady-state condition to be closely approached Care also must be taken to keep the signal level sufficiently low that limiting does not occur in the coupler

Since sinusoidal signal generators for the frequency spectrum in question were not readily available, a suitable generator was constructed for the purpose It provides a sine wave signal having a frequency adjustable between 0 0002 cps and 6 cps, and an amplitude adjustable between zero and 100 millivolts Two views of this experimental generator are shown in Fig 2 The principles of operation of the generator can be readily understood by reference to Fig 3 which is a block diagram of the unit

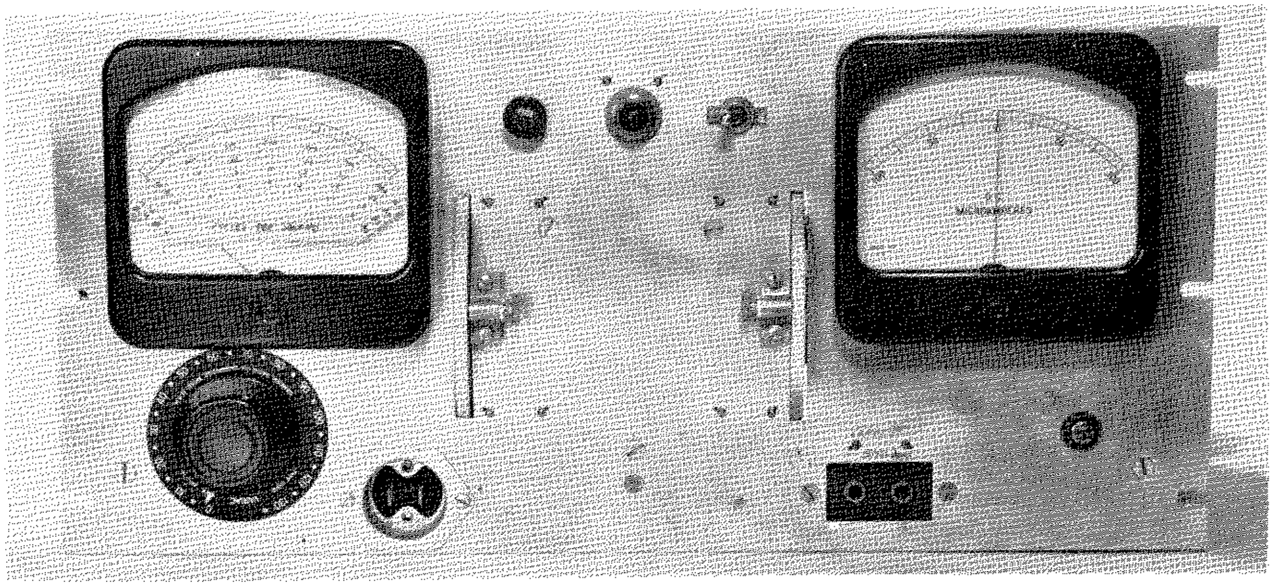
To illustrate the general nature of the transfer-functions of automatic approach couplers, Figs 4 and 5 show magnitude and phase of transfer functions for a localizer and glide channel respectively These curves were taken with the experimental low-frequency generator and an early model Minneapolis-Honeywell coupler This coupler was, incidentally, the one mentioned earlier which was modified in the glide channel to use the rate method of stabilization

While the transfer function of the coupler defines the performance of the coupler, and facilitates the comparison of one coupler with another, it does not, in itself, define the performance of the automatic approach system The complete system control loop actually includes the radio-produced course line, the receivers, the coupler, the automatic pilot, the airplane, the geometry of flight, and finally again the radio-produced course line Thus, the performance of the control system may be defined by specifying a transfer function for the entire loop The course line and receiver portions of the loop have fairly well known and relatively fixed characteristics In the case of the autopilot-airplane combination, however, it is a different matter Airplane characteristics vary considerably with type, particularly with regard to response time in the roll axis Autopilots have widely different values of turn sensitivities, that is, one autopilot may produce a coordinated 20° banked turn in response to a 4-volt turn signal, while another autopilot of different manufacture may produce the same turn in response to a turn signal of only one-tenth of that value The use of a slowly precessed directional gyro further complicates the transfer function in the case of some autopilots It appears then that it would be quite desirable to be able to measure a transfer function for the combination of coupler, autopilot, and airplane Then by applying the characteristics of the course line, the radio receivers and the geometry of flight, one could arrive at an accurate transfer function for the entire loop

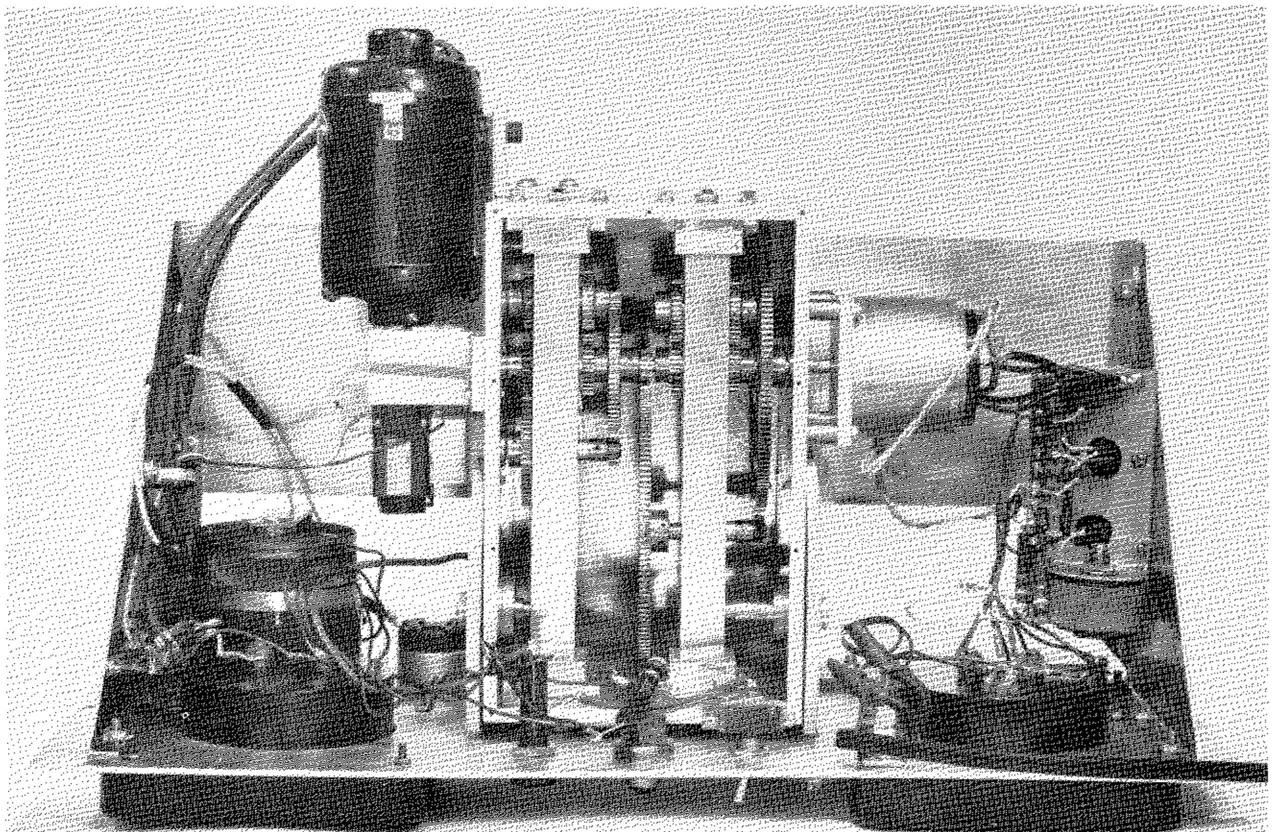
A block diagram of a suggested test equipment for obtaining the combined transfer function is shown in Fig 6 The equipment is airborne, and measurements would have to be made under actual flight conditions

The procedure would be to disable the radio receivers, and clip the output of the low-frequency generator across the terminals of the crosspointer, on the axis to be tested The autopilot would be turned on and engaged as for an automatic approach Then, by simultaneously recording the generator output, constituting the forcing signal, and the position of the attitude gyro, constituting the response, one could obtain the combined transfer function

As mentioned previously, one can ex-



(A) FRONT VIEW



(B) TOP VIEW

Fig. 2 Experimental Low Frequency Generator

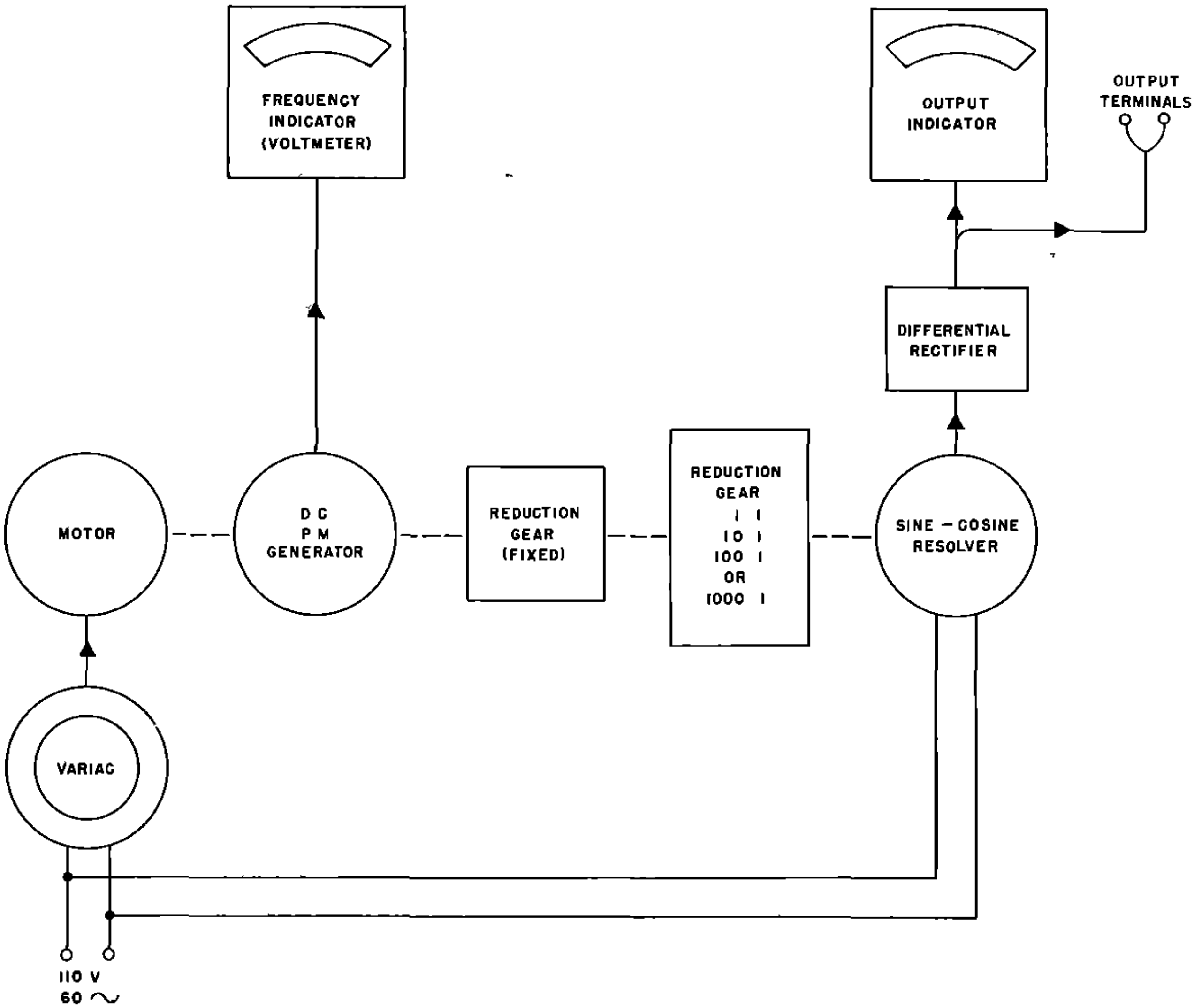



Fig 3 Block Diagram of Experimental Low Frequency Generator

pect to deduce the entire loop transfer function, once the combined coupler, autopilot and aircraft function is known Having this, it is then possible to predict stability or instability, and further, to estimate damping factors and resonant frequencies, and evaluate the effects of fluctuations in the position of the course line

## EXTENSION OF AUTOMATIC APPROACH TO TOUCHDOWN

At the present state of the art, it is possible, using commercial equipment, to demonstrate repeatedly satisfactory automatic low approaches to an altitude of about 50 feet, at which point the pilot usually will be in visual contact with lights or runway, and can complete a landing manually Completely automatic landings however, are quite another matter, and are yet a considerable distance from the realm of practicality At present, the next logical step to be taken toward the achievement of automatic landing would appear to be the extension of the autopilot control to the point of touchdown

The problems associated with the two axes, azimuth and elevation, may be considered separately In azimuth, using present commercial automatic approach equipment on an average localizer, the performance is very nearly good enough to permit auto-

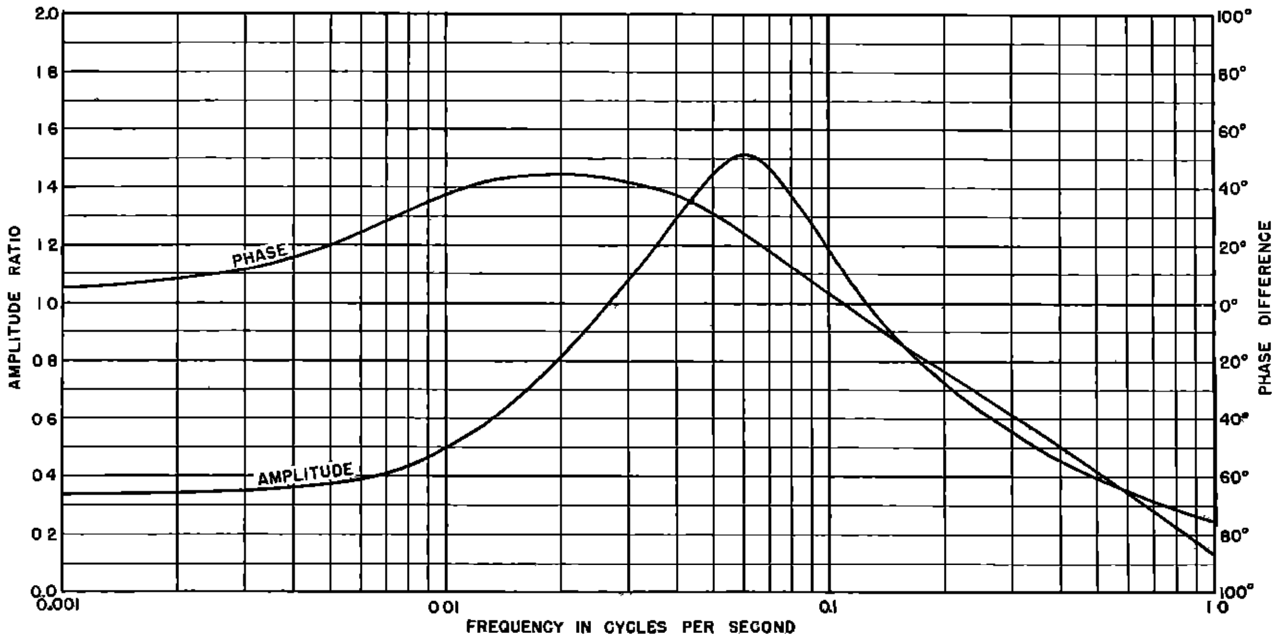



Fig 4 Transfer Function of Minneapolis-Honeywell Coupler CSX6442-Localizer Channel

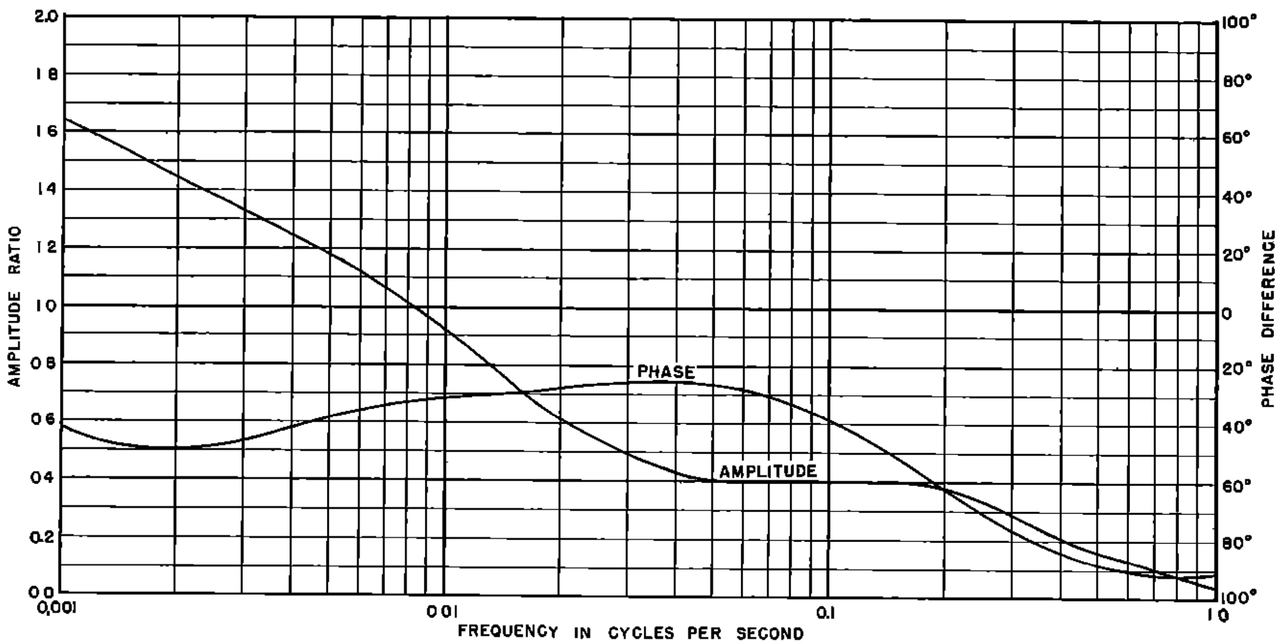



Fig 5 Transfer Function of Minneapolis-Honeywell Coupler CSX6442-Glide Channel

pilot control to touchdown In fact, it is good enough, if pains are taken to obtain a particularly straight localizer and the automatic approach equipment is in first-class condition This statement is supported by numerous automatic approaches to or very near touchdown which have been made at Indianapolis, all of which were comfortably within the boundaries of the runway pavement Fig 7 is a reproduction of a recording of localizer crosspointer deviation made when using automatic approach equipment on an experimental parabolic directional localizer at Indianapolis It is typical of a number of

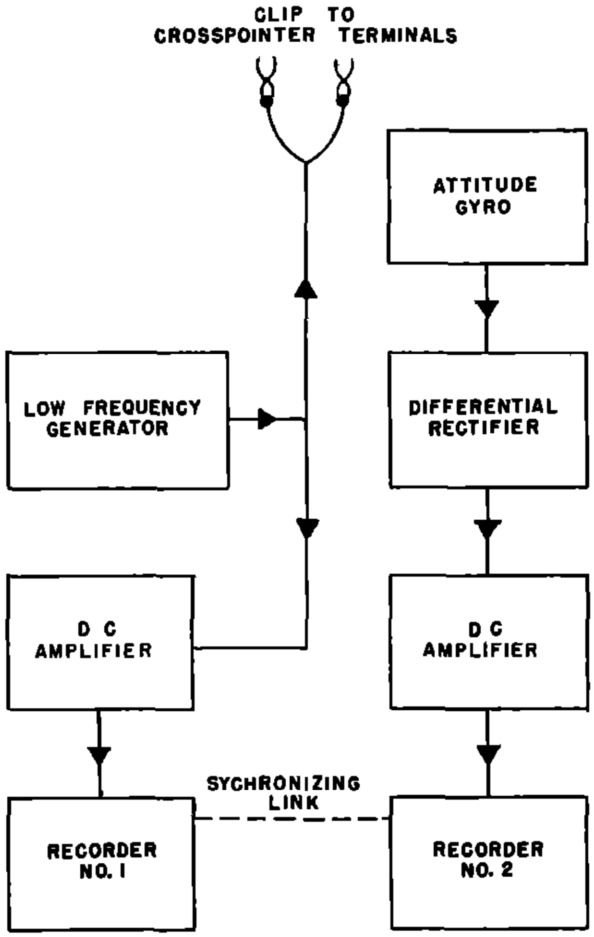



Fig 6 Block Diagram of Suggested Test Equipment for Obtaining the Combined Transfer Function

such recordings made under moderately smooth air conditions

The problem of control in elevation to touchdown is considerably more difficult When it is realized that the kinetic energy which must be taken up in the shock of touchdown is proportional to the square of the vertical speed, it is apparent that the rate of descent must be controlled within close limits This cannot be done if there is any tendency toward system instability in the region of high positional sensitivity in the glide slope just prior to touchdown Nor can it be done if the control has a response speed which is much slower than the speed of transient displacements introduced by turbulent air or other effects which may be encountered On the basis of experience to date, it is evident that for satisfactory control in elevation to touchdown, the general control system performance must be at least one order of magnitude better than is required for the automatic low approach

An airplane descending a 2 1/2° slope with a ground speed of 120 mph has an average rate of descent of 460 feet per minute Striking the runway at this vertical speed results in a tolerable but rather stiff jolt in most airplanes However, if due to turbulence or control system transients, there are variations in the rate of descent, which are superimposed upon the average value, then the total rate of descent at touchdown may be considerably greater than 460 feet per minute, and the resulting shock excessive Thus, it seems desirable to flare the approach path, and by this means to reduce the average rate of descent before touchdown

At this time, there are two basic methods under serious consideration for flaring the approach path The first involves the use of a radio altimeter which, at a predetermined low altitude, automatically takes over control, in lieu of the glide slope signal, and produces a smooth exponential approach to the runway This method is under development by the Department of the Air Force The second method is to actually modify the shape of the path produced by the glide slope projector, so that instead of being a straight line to touchdown, it is straight to about 50 feet altitude, beyond which point it has a gradually reducing slope This method is currently being investigated at the Technical Development and Evaluation Center The theory of the flared glide slope projector is discussed in a previously published report [6]

The production of the flare by means of modification of the glide slope projector has the advantage that no additional equipment is required in the airplane specifically for the flare Also, possible trouble due to failure of automatic switching at a crucial moment is avoided However, there are practical limitations on the shape of flare which

[6] C B Watts, Jr , "Theoretical Consideration of An Improved Glide Path Antenna System," Technical Development Report No 81, CAA, Indianapolis, March 1949

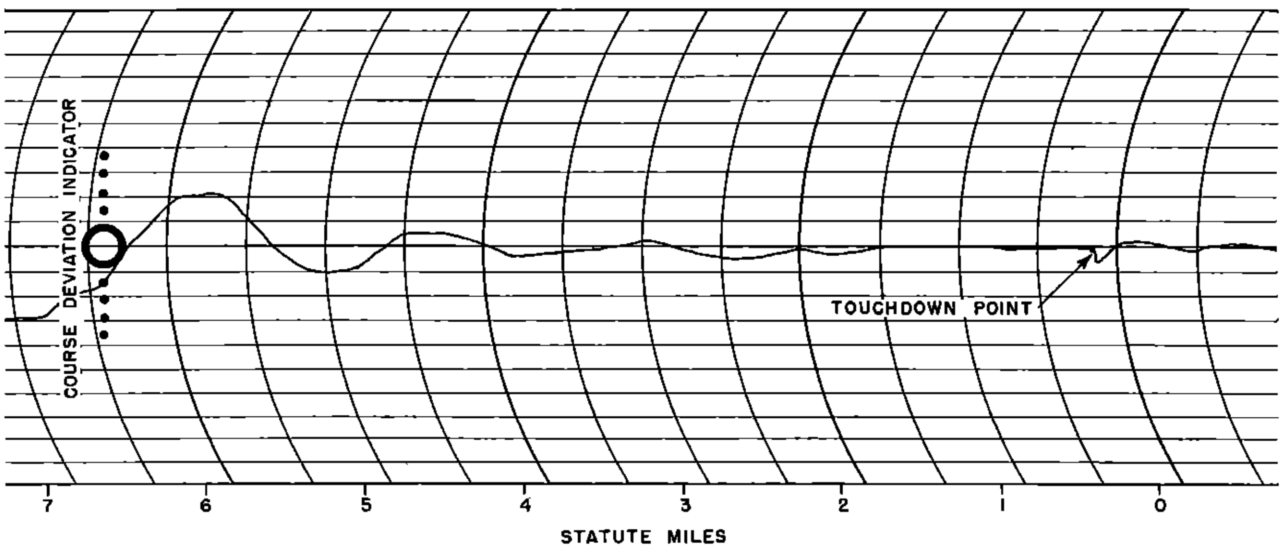



Fig 7 Localizer Crosspointer Deviation Recorded on Automatic Approach in NC-181 Using Experimental Parabolic Directional Localizer, Runway 36, Indianapolis, October 27, 1949

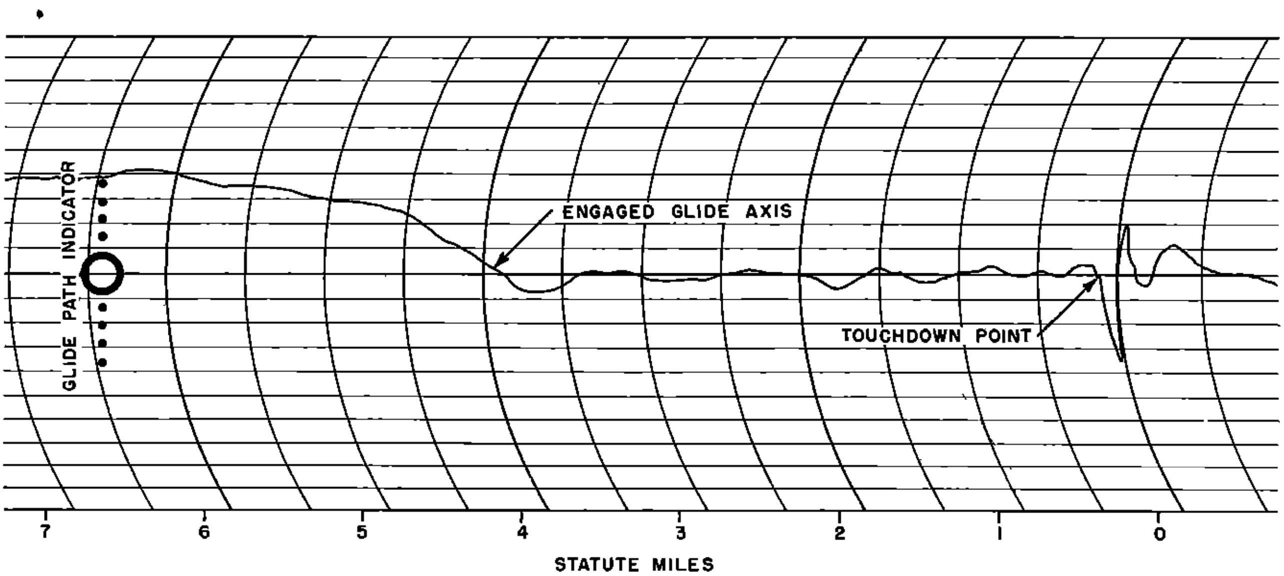



Fig 8 Glide Slope Crosspointer Deviation Recorded on Automatic Approach in NC-181 Using Experimental Null-Reference Flared Glide Slope, Runway 36, Indianapolis, October 27, 1949

can be produced in a glide slope, and the effects of antenna height variation between different airplanes must be considered

A flared glide slope projector has been built at Indianapolis, and is undergoing tests to determine the most desirable flare shape as well as the practicability of the method in controlling automatic flight to touchdown

Numerous approaches to touchdown using this equipment have been made with results somewhat variable, and dependent upon turbulence conditions and adjustment of the control characteristics of the automatic approach equipment in the airplane Fig 8 is a reproduction of a recording of the glide slope crosspointer deviation made on such an approach It is typical of that which can be obtained under moderately smooth air conditions and with the best adjustment of the automatic approach equipment The recordings in Figs 7 and 8 were made during the same approach From the glide slope deviation recordings similar to Fig 8 it is difficult to determine the rate of descent, or to tell much about the reduction in rate of descent caused by the flare, and no equipment for recording rate of descent was available However, a number of approaches to touchdown have been observed in which the rate of descent at touchdown was surely less than 200 feet per minute, resulting in a very mild impact To achieve freedom from the variable effects which were mentioned earlier it undoubtedly will be necessary to increase substantially the tightness of control, while maintaining system stability, and also to maintain a rigorous control over other important characteristics of the system such as the flare shape and autopilot behavior

A description of the experimental flared glide slope projector at Indianapolis is attached to this report as Appendix II

## RADIO-CONTROLLED FLIGHT ON OMNIRANGE AND COMPUTER COURSE LINES

With the implementation of the VHF omnirange and DME programs there is a growing interest in the adaptation of automatic approach equipment to provide radio-controlled flight on omnirange and computer course lines Thus far, there has been little work done in this direction However, it is likely that there will be no basic trouble in accomplishing the desired results, although it is probable that considerable modification of the control characteristics of the coupler will be required

The crosspointer positional sensitivity of a localizer at 10 miles has a value s = 60 microvolts per foot A typical value of rate parameter to provide critical damping at this distance on the localizer would be r = 24 seconds [7] An omnirange has an angular course width about five times that of the localizer Also, it is likely that one would choose to have critical damping at a distance more nearly 50 than 10 miles These two conditions combine to reduce the positional sensitivity by a factor of about 25, so that for the omnirange s = 2 4 microvolts per foot Since, with other parameters remaining constant the rate parameter for critical damping varies inversely as the square root of the positional sensitivity of the radio facility, the rate parameter for critical damping at 50 miles on the omnirange would have a value r = 120 seconds If, in addition, there is a reduction in the gain parameter of the coupler, an even larger value of rate parameter will be required to maintain critical damping

The requirement for such large values of rate parameter makes it very unlikely that a resistance-capacitance derived rate signal alone will be used for stabilization More likely sources are the slowly precessed directional gyro, or a combination of gyro and rate signal The latter source in particular offers the possibility of obtaining near optimum damping over a wider range of positional sensitivity This matter is further discussed in Appendix III of this report

The problems of automatic flight control on computer course lines are quite similar to those associated with flying the omnirange course lines, with one important simplification While the omnirange courses are of constant angular width, resulting in changing positional sensitivity with distance, the computer course lines normally have a constant linear width, which means a constant positional sensitivity throughout the entire length of the course line This has the desirable result of eliminating the effect of distance on the control system stability

## CONCLUSIONS

Substantial progress has been made in the field of radio-controlled flight with regard to the commercial production of automatic approach equipment More attention needs to be paid, however, to methods for testing and standardizing the performance of such equipment prior to radio-controlled flight becoming an established part of instrument flight procedures

Further improvements in ILS facilities, together with considerable tightening of autopilot control characteristics, will be required before the extension of automatic approach to touchdown can become a practical reality

Radio-controlled flight on omnirange and computer course lines is technically feasible and should receive attention when the operational need for it exists

[7] See footnote 1

## APPENDIX I

### A Method of Automatic Glide Path Control

The following is a description of some work that was done in December, 1947 at the CAA Technical Development and Evaluation Center regarding a glide path automatic control which does not exhibit residual error due to fore-and-aft mistrim

Thus far, the most widely used method of control had been what may be termed "displacement versus pitch angle " In this method the glide path displacement signal is converted to an alternating voltage, amplified, and fed to the elevator axis bridge circuit, where it produces a proportional departure of the pitch angle from its reference or zero signal value This method provides a smooth and non-oscillatory control down to the contact, provided the ratio of the pitch angle to displacement is not made too high It suffers, however, the annoying drawback that a residual off-path error is present whenever the reference or zero signal pitch angle differs from that pitch angle which would be required to bring the airplane down the center of the path in the absence of automatic control It is difficult, manually, to preset the correct reference pitch angle, and even if this could be done, the correct reference is subject to changes without notice on the way down These changes in reference angle are brought about by a number of factors affecting fore-and-aft trim, such as operation of flaps, and landing gear, changes in engine power, movement of passengers, and changes in wind velocity Increasing the ratio of pitch to displacement reduces the residual error for a given mistrim, but this ratio cannot be raised above a value which, with the unavoidable airplane inertia, induces hunting close to the point of contact The control is a weak one at best, requiring careful monitoring and adherence to standard conditions Considered at its worst, it is almost no control, since it can be completely overridden by changes in power and trim setting

A number of years ago, at Wright Field, F L Moseley suggested disconnecting the pitch axis gyro signal when using the glide path control This would have the effect of eliminating the reference pitch angle A given glide path displacement would simply result in a corresponding elevator surface deflection Presumably, each elevator deflection would produce a corresponding rate-of-change of pitch angle With the addition of a rate circuit to the coupling unit, this method would provide a glide path control directly analogous to that which is commonly used on localizers This may be termed a "rate method " There would still remain some possibility of residual error due to incorrect choice of the zero signal position of the elevator surface, but such error would probably be quite small The method as stated above has the characteristic that if equilibrium with the glide path is not reached, the airplane will continue changing pitch angle without limit For this reason primarily, the method was never tried in this form

The method which was tried is a slight variation of the method proposed by Moseley, and was made easy of accomplishment by a Minneapolis-Honeywell coupling unit which used a servo-driven potentiometer to introduce pitch displacement signals into the elevator axis bridge Prior to modification, this unit operated on the conventional "displacement versus pitch angle" method The servo included a position feedback potentiometer, and a speed feedback generator to prevent overshoot By disconnecting the position potentiometer, and increasing the feedback from the speed generator, the rate-of-change of the pitch angle was made proportional to the amplifier input The addition of a suitable rate circuit ahead of the amplifier substantially completed the modification The method of control may now be stated as follows Glide path displacement plus rate-of-change of glide path displacement produces a corresponding rate-of-change of pitch angle There is, however, an important limitation to the above statement, namely, it holds true only until the servo-driven potentiometer strikes its stop Thus, although there is no longer a specific reference or zero-signal pitch angle, there are definite positive and negative limits on pitch angle which keep the airplane within a safe attitude regardless of signal input to the coupling unit. Theoretically, as long as the potentiometer limits are not reached, the control will stabilize without residual, with no regard to the trim conditions

This rate method control was in use for several months in a DC-3 type airplane

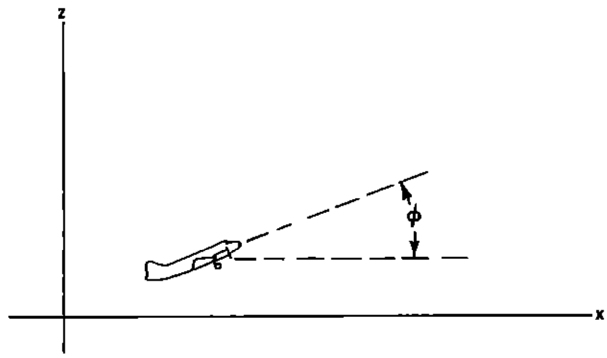



Fig 9 Glide Path Control, Definition of Coordinates

It demonstrated reasonable agreement with the theory For example, flaps or landing gear could be operated after the final approach had started without upsetting the operation On several occasions, operation was observed while one or two persons moved from the rear of the cabin up to the cockpit The resulting change in trim introduced transients, but did not prevent the airplane from settling back on the path The installation did not include throttle control The power was set to produce the desired airspeed, and was left unchanged unless there was a significant change in speed

A brief comparison of the two control methods on a theoretical basis follows

Fig 9 illustrates an airplane, viewed in elevation, in relation to z and x axes, the x axis being assumed coincident with the glide path The angle $\phi$ is the angle made by the direction of motion of the center of gravity and the path axis It is positive for nose-up attitudes

Fig 10 shows, in block schematic, a "displacement versus pitch angle" control A group of equations describing the operation of the control can be written as follows If the airplane has a speed, v, and the angle $\phi$ always remains small

$$\dot{z} = v \sin \phi \approx v\phi \quad (1)$$

$$\dot{x} = v \cos \phi \approx v \quad (2)$$

The output of the glide path receiver is given by

$$e_1 = \sigma z \quad (3)$$

where $\sigma$ is the positional sensitivity in volts per foot The filter network $R_f C_f$ is used to simulate the lumped inertia lags of the airplane and autopilot, and a small filter network which may be used If it has a time constant $\tau$ seconds, then

$$e_2 + \tau \dot{e}_2 = e_1 \quad (4)$$

The voltage $e_2$ fed into the amplifier, thence to the elevator bridge, causes a proportional departure in the pitch angle from a reference $\phi_o$

$$\phi - \phi_o = -g e_2 \quad (5)$$

where g is the amplifier-autopilot gain constant in radians per volt Note that the correction is polarized to rotate the nose of the airplane toward the path

Combining the five above equations yields the following

$$\tau \ddot{z} + \dot{z} + g v \sigma z = v \phi_o \quad (6)$$

which is a differential equation of the airplane displacement from the path It may or may not describe oscillatory motion For critical damping

$$\tau \sigma = \frac{1}{4gv} \quad (7)$$

Typical values for gain and speed constants are

$g = 0\ 44$ rad /volt
$v = 200$ ft /sec

Thus,

$$\tau \sigma = 0\ 00282 \frac{\text{volt-sec}}{\text{rad -ft}}$$

This equation defines, for a given time lag, the maximum positional sensitivity which may be present before overshooting begins For example, suppose we consider that a time lag of one second exists Then, $\sigma = 0\ 00282$ volts/ft For a glide path having a full scale voltage of $e_1 = \pm 0\ 15$ volts at $\pm 0\ 8°$ from center, this positional sensitivity corresponds to a distance of 3,820 feet from the station Inside this distance there is overshooting, unless glide path softening is used to reduce the positional sensitivity sufficiently

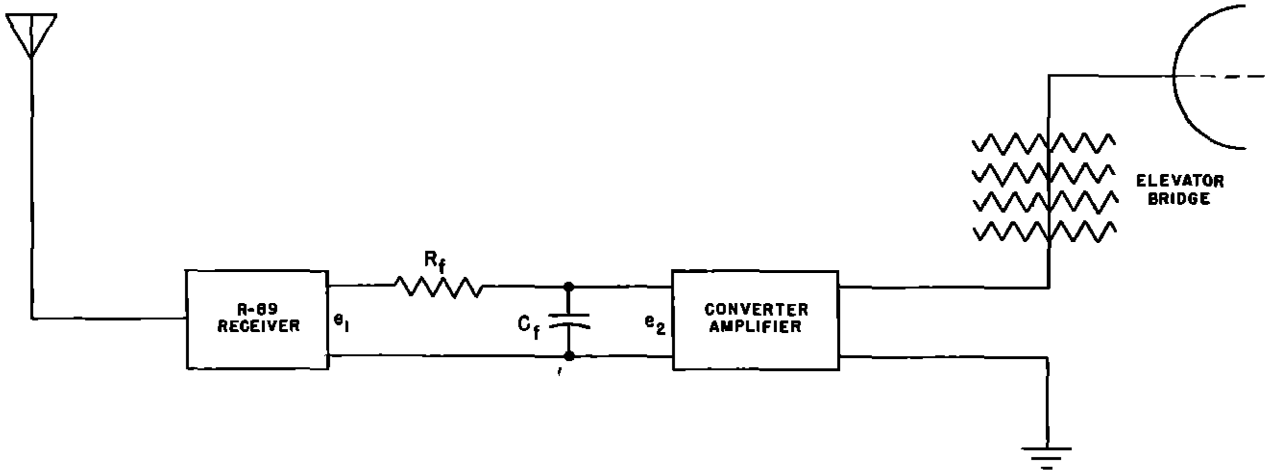



Fig 10 Block Diagram, Conventional Pitch-Displacement Method

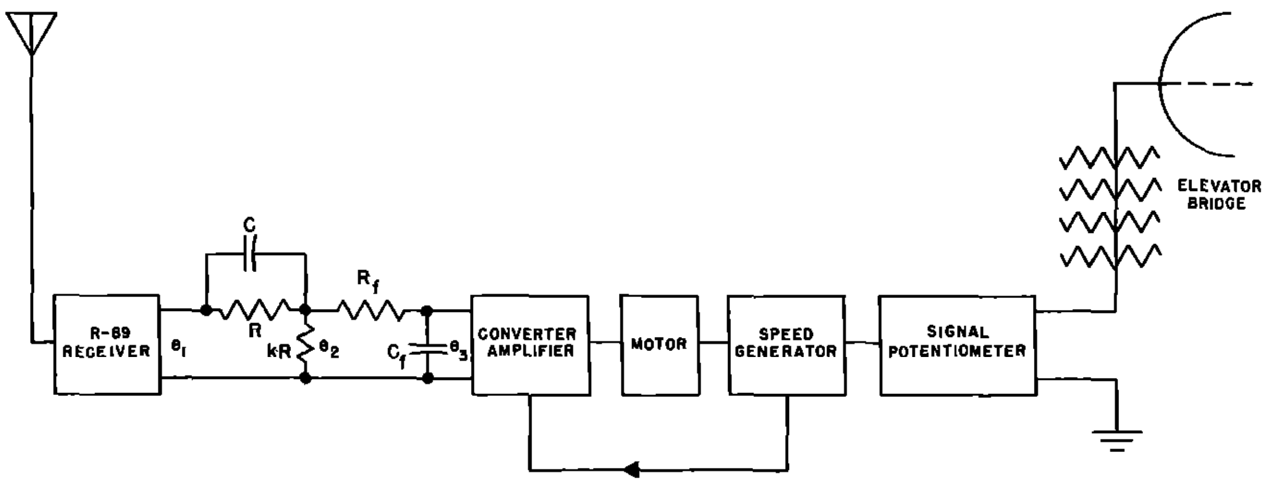



Fig 11 Block Diagram, Rate Method

It is of interest to examine the residual error at 3,820 feet from the station Note that in equation (6), the right hand member is not zero, but has a value dependent on the reference pitch angle Thus, even when the values of z and z have closely approached zero, there must remain a residual z on the left side of the equation In the example chosen, the residual is

$$z_\epsilon = \frac{\phi_o}{\sigma g} = 806\ \phi_o = 14\ 1\ \phi_o{}^\circ \text{ feet} \qquad (8)$$

that is, for each degree error in reference pitch angle, the airplane will stabilize in error by 14 1 feet at a distance where the full scale displacement would be 53 2 feet

Fig 11 shows, in block schematic, the "rate method" control which has been described. A similar set of equations describing this system can be written

$$\dot{z} = v \sin \phi \approx v\phi \qquad (1)$$
$$\dot{x} = v \cos \phi \approx v \qquad (2)$$
$$e_1 = \sigma z \qquad (3)$$

The output of the rate circuit is given to good approximation by

$$e_2 = k\,(e_1 + \rho \dot{e}_1), \quad k \ll 1 \qquad (9)$$

where $\rho$ is the time constant RC of the rate circuit

As before, the circuit $R_fC_f$ represents the inertia and filter lags, and the time constant is $\tau$

$$e_3 + \tau\dot{e}_3 = e_2 \tag{10}$$

The voltage $e_3$ is applied to the amplifier, and, by virtue of the speed generator, produces a proportional speed of shaft rotation The signal potentiometer attached to the shaft produces a corresponding rate-of-change of pitch angle This whole effect is summed up in the equation

$$\dot{\phi} = -ge_3 \tag{11}$$

where g is a gain constant having the dimensions $\frac{\text{rad}}{\text{volt-sec}}$ Combining the six foregoing equations

$$\tau\dddot{z} + \ddot{z} + \gamma v\rho\dot{z} + \gamma vz = 0 \tag{12}$$

where $\gamma = \sigma kg$

which is a differential equation describing the motion This can be solved using cubic formulae, but for most purposes, $\tau$ is sufficiently small to permit the first term to be neglected Then,

$$\ddot{z} + \gamma v\rho\dot{z} + \gamma vz = 0 \tag{13}$$

This is identical with the differential equation for motion which is obtained in rate method localizer control The right hand member of the equation is zero, and there is accordingly, no residual error. For critical damping,

$$\rho = \frac{2}{\sqrt{\gamma v}} \text{ sec} \tag{14}$$

The period of oscillation with rate condenser omitted is

$$T = \frac{2\pi}{\sqrt{\gamma v}} \text{ sec} \tag{15}$$

It may be of interest to determine a value of rate constant $\rho$ for critical damping, using typical parameters of the equipment which has been flown

$k = 0\ 05$ numeric
$v = 200$ ft /sec
$g = 0\ 25$ rad /volt-sec
$\sigma = 10\ 7\frac{1}{x}$ volts/ft

where x is distance from station in feet Thus

$$\rho = \frac{2}{\sqrt{\gamma v}} = \frac{2}{\sqrt{\sigma kgv}} = \frac{2}{\sqrt{\frac{10.7}{x}kgv}} = 0\ 387\sqrt{x} \text{ sec}$$

Then, for example, to have critical damping at one mile from the station

$x = 5280$ feet
$\rho = 0\ 387\sqrt{5280} = 28$ sec

A considerably smaller value of rate constant than that calculated above was used in the experiments There is considerable work yet to be done in determining optimum parameters Even so, it can be stated that the rate method appears to be a superior one regarding both smoothness of control and tenacity of holding to the path in conditions of turbulence and changing trim

## APPENDIX II

### Description of Flared Glide Slope Equipment

In January, 1948, construction was begun on an experimental flared glide slope antenna array following the theory described in an earlier publication.[8]

An AN/CRN-2 transmitter-modulator was made available as a source of modulated rf power for the antenna array. The transmitter had previously received considerable modification in connection with a study of means of increasing tube life in the power output stage.[9] In adapting this transmitter-modulator to the new antenna system, it was necessary to construct new stator blades for the 150 cps modulation trough in order to bring up the power level, equal to that of the 90 cps trough; and, in addition to provide balun converters to RG-8/U cable at the trough outputs.

The antenna system was first set up to reproduce the path shape labeled Case III.[10]

[8]See footnote 6

[9]C. H. Jackson, "Improvements in Glide Path Transmitters," Technical Development Report No. 91, April 1949.

[10]See footnote 6

This is a hyperbola, tangent to the runway. It was very soon found experimentally, however, that the flare in this path occurred much too late in the approach and too rapidly to be of any practical value in flight. It was, therefore, decided to add a second modifier antenna pair for the purpose of causing the flare to begin earlier in the approach and to change the slope more gradually. The combined modifier pattern would then have the form:

$$F_M = [A_1 \sin(S_1 \sin\theta) + A_2 \sin(S_2 \sin\theta)] \sin\left(\frac{\pi}{2}\frac{\phi}{\phi_o}\right)$$

in which $A_1$ and $A_2$ are the amplitudes and $S_1$ and $S_2$ the half spacings of the first and second modifier antenna pairs respectively.

A prefabricated antenna bridge and distribution harness for feeding the antenna array was constructed of RG-8/U cable, using semi-permanent type T fittings, and is illustrated in Fig. 12. The antenna array is shown in Fig. 13. The top or null antenna is approximately 34 feet above the ground, to produce a 2 1/2° glide angle. In Fig. 14, a close-up of the carrier antenna and modifier group more clearly shows the details of antenna construction. The individual elements of the modifier group were provided with slots and rows of mounting holes in order to facilitate adjustment of the modifier antenna pattern to change the flare shape.

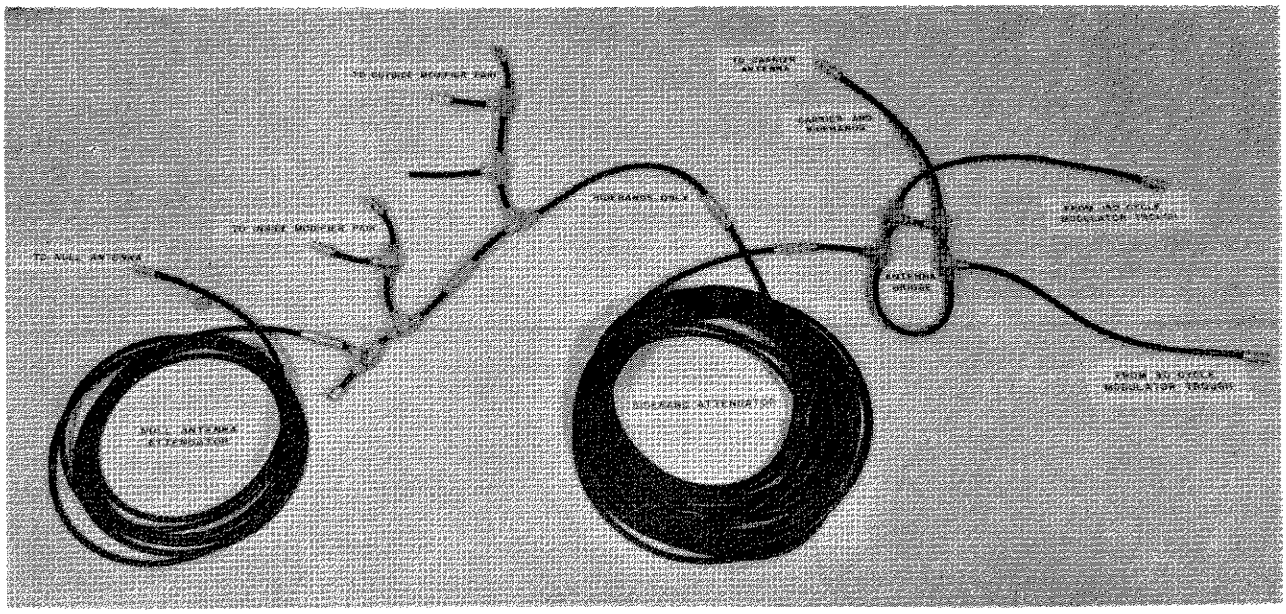


Fig. 12 Antenna Bridge and Harness for Null Reference Glide Path

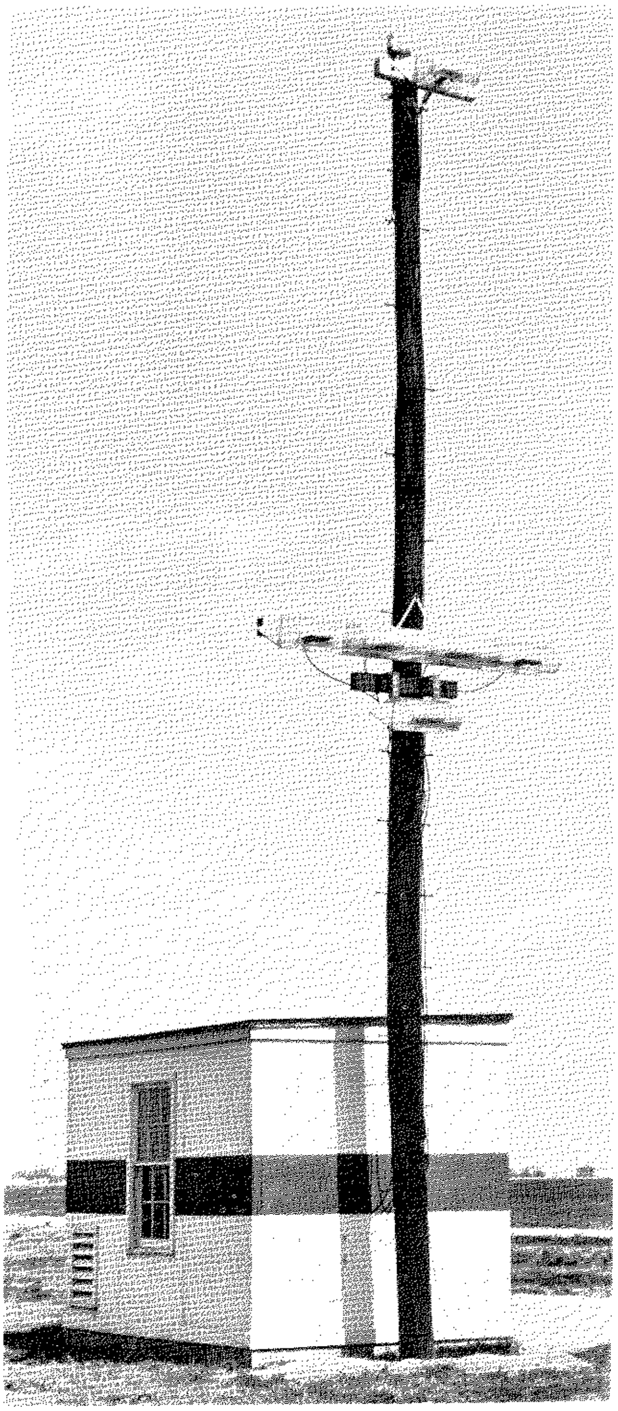


Fig. 13 Null Reference Flared Glide Slope Antenna Array

In monitoring or antenna pattern measurements with an antenna system of this type, it is necessary to consider the phasing error due to proximity, which exists between the energy received from the null antenna and the energy received from the carrier and modifier antennas. The magnitude of the phasing error is given by the formula

$$\alpha_\epsilon = \frac{1}{2r}(h_1^2 - h_2^2)\frac{360}{\lambda} \text{ degrees}$$

in which r is the distance between the antenna array and the receiving point, $h_1$ and $h_2$ are the heights of the upper and lower antennas above ground, and $\lambda$ is the wavelength. With a receiving point located about 275 feet from the array, the phasing error is 180°. This condition results in a combination of patterns to produce a path which is reversed in sensing, but in other respects the patterns are substantially the same as those which would be measured at great distances. It was, therefore, decided to make pattern and monitoring measurements at this distance. The null antenna was displaced horizontally toward the runway a distance of 11 inches to eliminate proximity phasing error at the airplane.

Separately exciting the null and carrier antennas resulted in measured field patterns in the vertical plane which are shown plotted in Fig. 15. With the entire antenna system fed through the distribution harness, as for normal operation except that one modulation trough is disconnected, the combined patterns shown in Fig. 16 were measured. These represent the distribution of 90 and 150 cps sidebands in the vertical plane at the point 275 feet directly in front of the station.

Field patterns in the horizontal plane also were measured and are shown plotted in Fig. 17 for the first and second modifier pairs. The element half-spacings are $S_1 = 130°$ and $S_2 = 396°$. In Fig. 18 are plotted the patterns measured for the carrier antenna, and for the total modifier group.

In September, 1948, a series of measurements was made to determine experimentally the path shape over the runway, using a portable mast on loan from the Wright-Patterson Air Force Base. A typical set of data is shown plotted in Fig. 19, for modifier half-spacings $S_1 = 146°$ and $S_2 = 396°$, and with a ratio of second pair current to first pair current of 0.15.

Ground monitoring antennas for the null-reference flared glide slope are located at three positions; first, directly ahead of the station 275 feet and approximately 12 feet above the ground for monitoring the path angle; second, directly under the first at a height of approximately six feet for monitoring the clearance and for use in phasing the rf energy to the null antenna; and third, about 60 feet to the side away from the runway from the first two monitoring locations, 275 feet from the station, and approximately four feet above the ground in an equal signal zone, having the purpose of monitoring path shape in the flared region. The energies from the monitoring antennas are fed back to the transmitter house, rectified in a germanium crystal detector circuit, amplified, filtered, and the 90 and 150 cps amplitude differences metered.

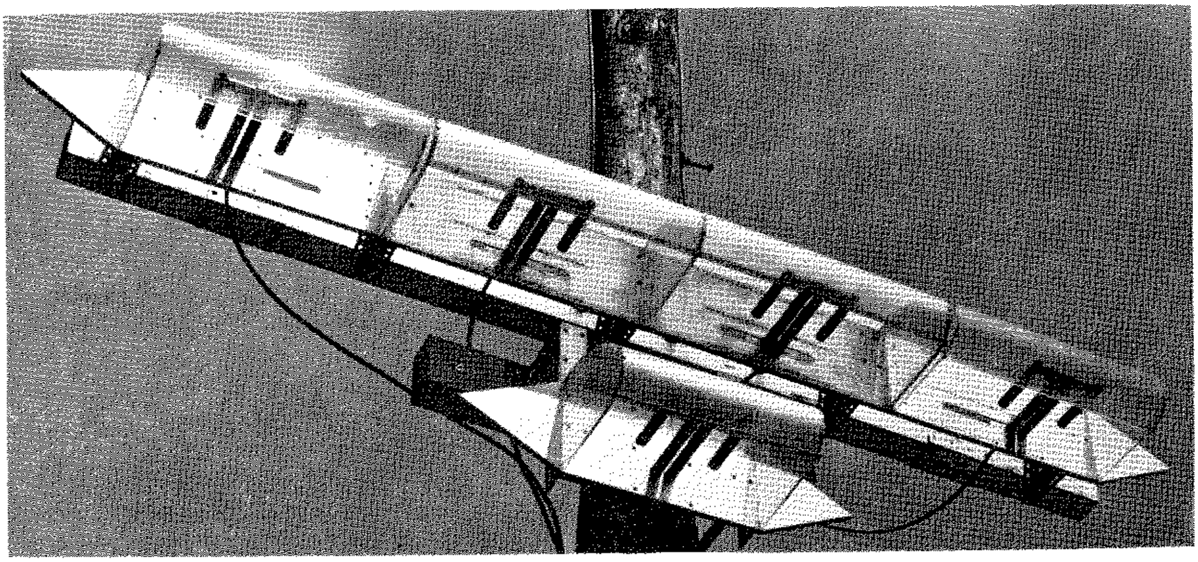


Fig. 14 Carrier Antenna and Modifier Group

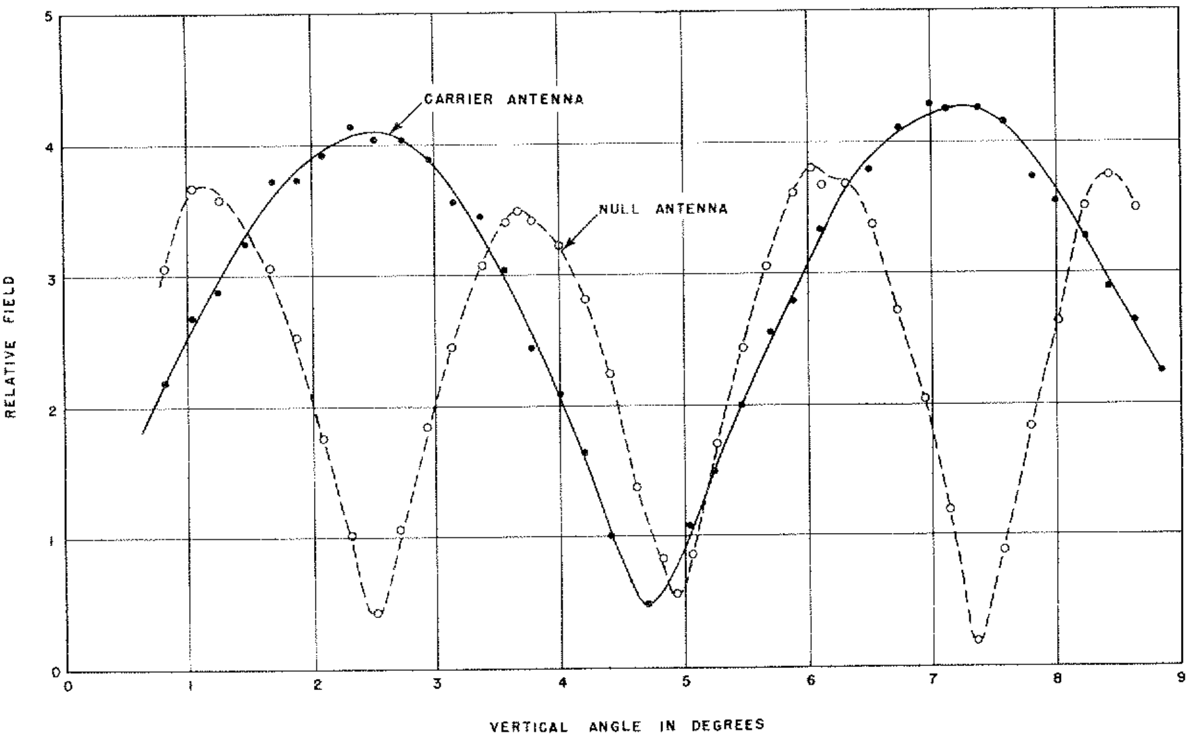



Fig. 15 Measured Field Patterns, Vertical Plane, Carrier and Null Antennas

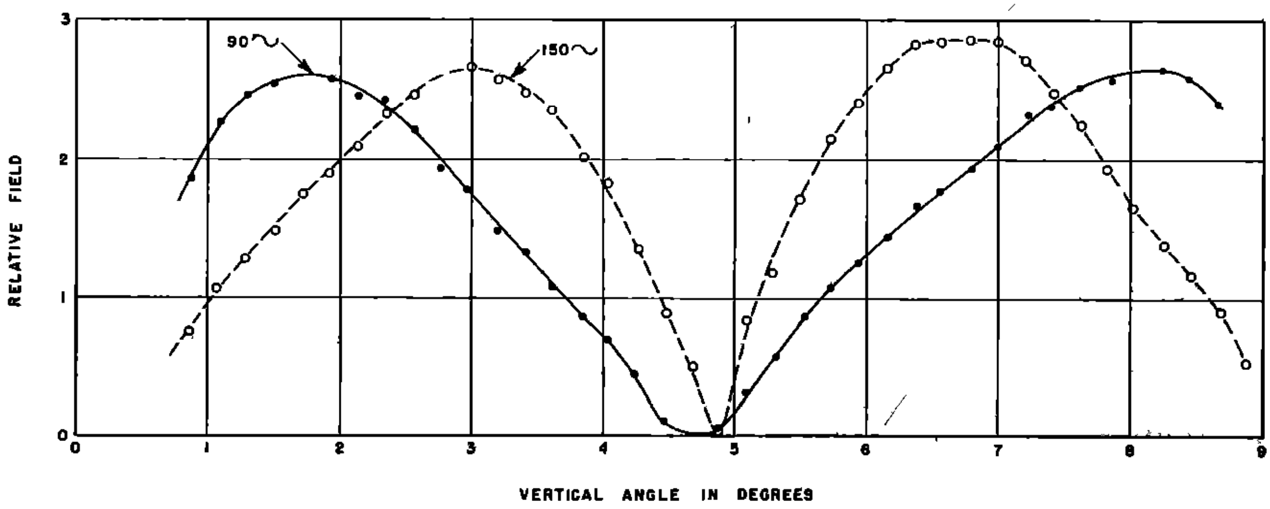



Fig 16 Measured Field Patterns, Vertical Plane, Entire System, 90 and 150-cps Components

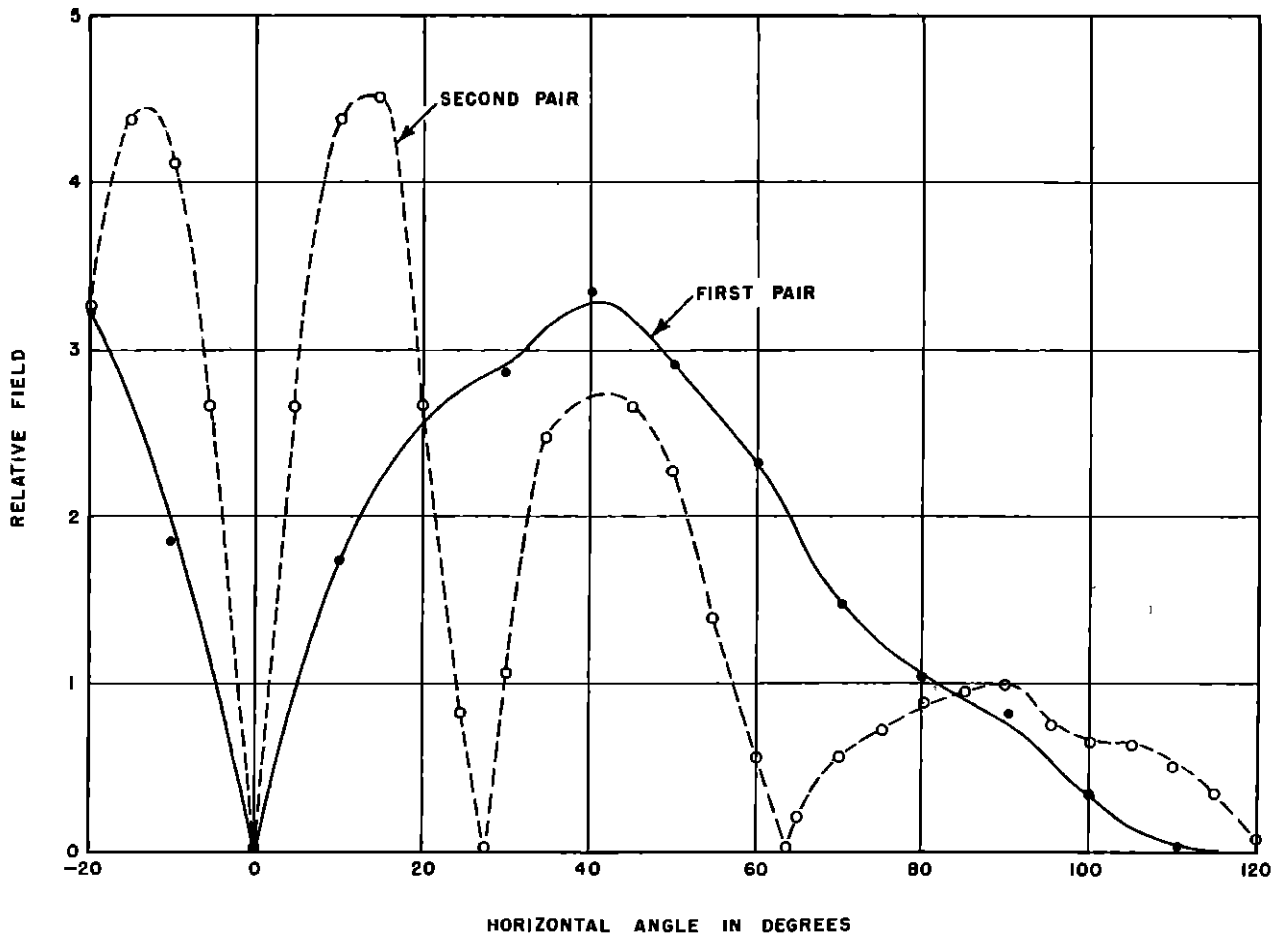



Fig 17 Measured Field Patterns, Horizontal Plane, First and Second Modifier Pairs

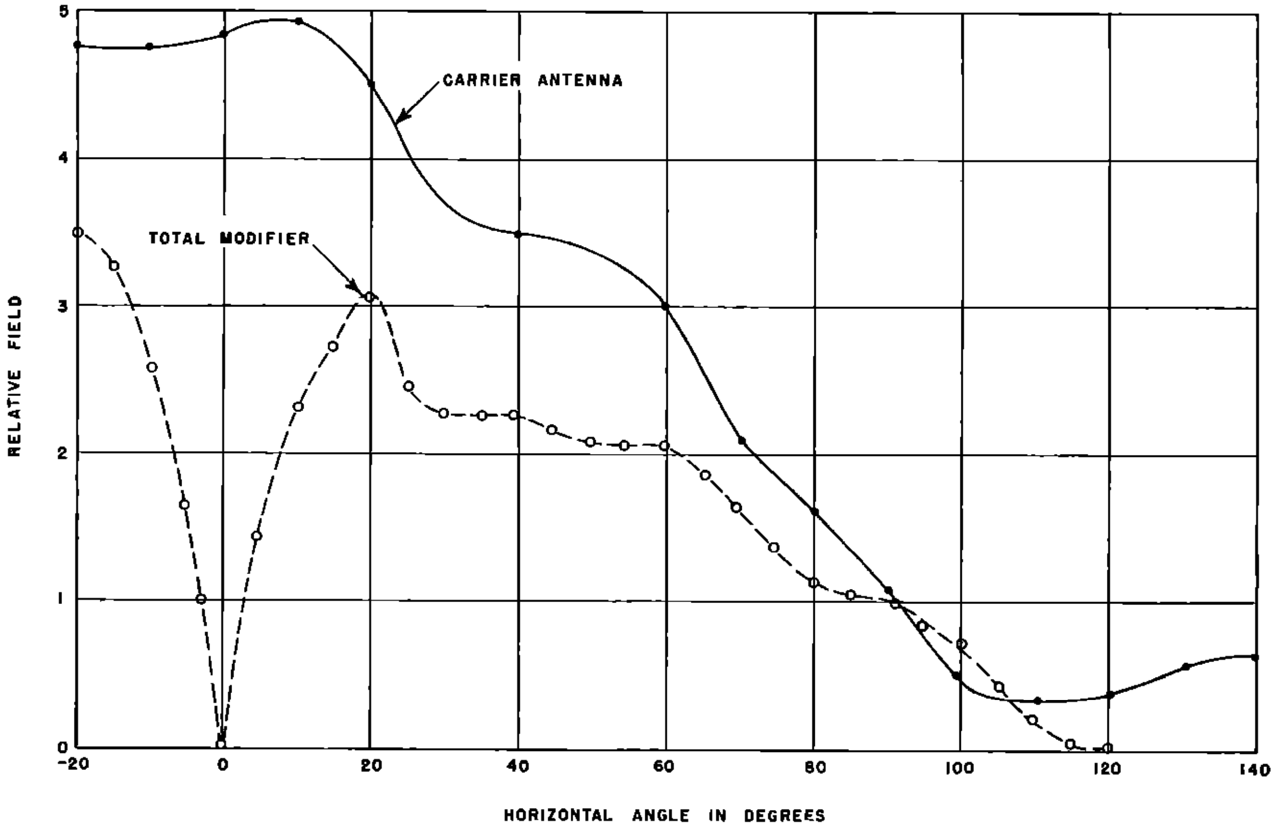



Fig 18 Measured Field Patterns, Horizontal Plane, Carrier Antenna and Total Modifier Group

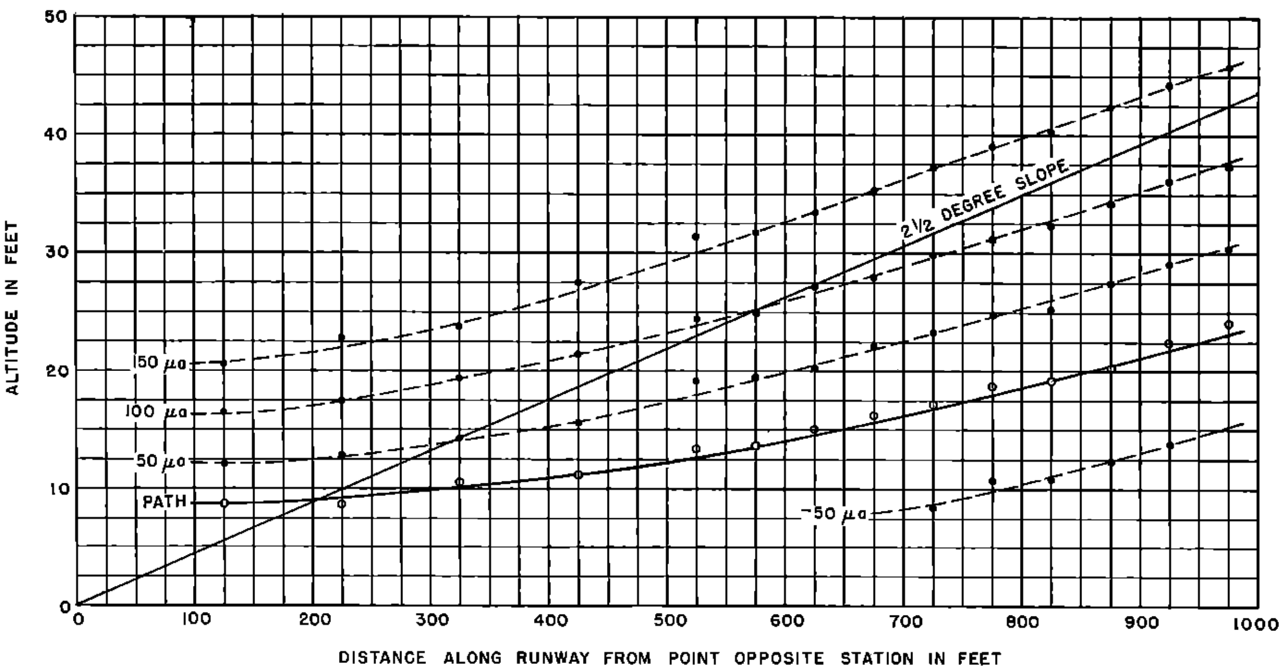



Fig 19 Measured Path Shape over Runway, Using Portable Mast and R89 Receiver, September 10, 1948

## APPENDIX III

### Calculations of Stability, Using Combined Gyro and Rate Signals in Flying Omnirange Courses

Referring to Figs 20 and 21, the following control equations can be written

$$e_1 = sy \tag{1}$$

where $e_1$ is crosspointer voltage in volts y is course line displacement in feet

$$e_2 = k\,(e_1 + r\dot{e}_1) \tag{2}$$

where $k << 1$ and $r = RC$ in seconds

$$e_\theta = \delta\,(\theta - \theta_o) \tag{3}$$

where $\theta_o$ is initial or reference heading

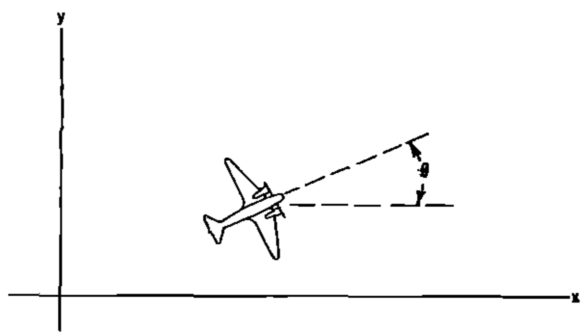



Fig 20 Azimuth Control on Omnirange Course, Definition of Coordinates

$$e_3 = e_2 + e_\theta = ke_1 + kr\dot{e}_1 + \delta\theta - \delta\theta_o \tag{4}$$

$$-\dot{\theta} = ge_3 \tag{5}$$

where g is the turn sensitivity of the autopilot in radians per second per volt Combining equations (1), (4), and (5)

$$-\dot{\theta} = skgy + skg\dot{y} + \delta g\theta - \delta g\theta_o \tag{6}$$

If in this derivation it is assumed that there is no crosswind, and the heading angle is always small, then

$$\dot{y} = v\theta \tag{7}$$

$$\ddot{y} = v\dot{\theta} \tag{8}$$

where v is the airspeed in feet per second
Substituting equations (7) and (8) in equation (6)

$$\ddot{y} + (skgvr + \delta g)\,\dot{y} + skgvy = \delta gv\theta_o \tag{9}$$

which is a differential equation for displacement as a function of time From this, note that for a reference heading $\theta_o$ there is a residual displacement error $y_\epsilon$,

$$y_\epsilon = \frac{\delta gv\theta_o}{skgv} = \frac{\delta}{sk}\,\theta_o \tag{10}$$

For determining transient response, equation (9) may be rewritten with the right hand member set to zero

$$a\ddot{y} + b\dot{y} + cy = 0 \tag{11}$$

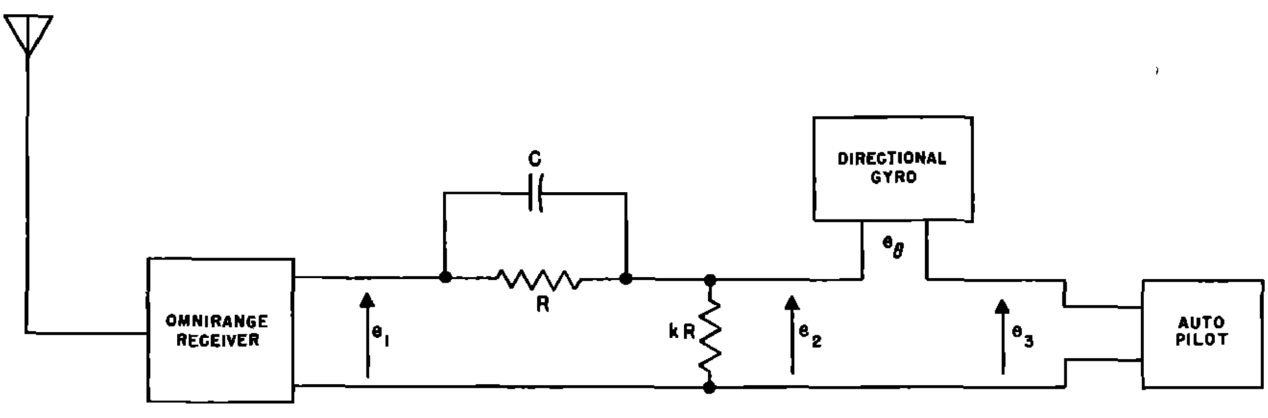



Fig 21 Azimuth Control System Block Diagram

where the coefficients

$a = 1$
$b = skgvr + \delta g$
$c = skgv$

and in which for critical damping

$$b^2 - 4ac = 0 \qquad (12)$$

or damping factor

$$D = \frac{b}{2\sqrt{ac}} = 1 \qquad (13)$$

and substituting the values of the coefficients

$$D = \frac{1}{2} r \sqrt{skgv} + \frac{1}{2} \delta g \frac{1}{\sqrt{skgv}} \qquad (14)$$

Typical values for some of the parameters are given as follows

$k = 0\ 05$ numeric
$g = 11\ 7$ rad /volt-sec
$v = 200$ ft /sec
$s = \frac{0\ 00012}{x}$ volts/ft for an omnirange course, where x is distance from station in miles

Substituting these values in equation (14) for the damping factor

$$D = 0\ 059 \frac{r}{\sqrt{x}} + 49\ 6\ \delta \sqrt{x} \qquad (15)$$

Note that the damping factor comprises two terms, one attributable to the rate circuit and the other to the directional gyro These two terms are shown plotted individually in Fig 22, for several values of rate parameter r and gyro parameter $\delta$ If tolerances of 0 5 to 2 0 are set on damping factor, it is observed that no one value of rate or gyro parameter, used separately, will provide proper damping over the desired distance range In Fig 23, however, a combined damping factor is plotted, which is the sum of the rate and gyro terms, for values of $r$ = 15 seconds and $\delta$ = 0 003 volts/radian It is interesting to note that the combined damping factor remains within the tolerances over a much greater range of distances

The magnitude of the residual displacement error which is introduced with the use of directional gyro signal for part of the stabilization, may be calculated as a function of the reference heading with equation (10), as follows

$$y_\epsilon = \frac{\delta}{sk} \theta_0 = \frac{0\ 003}{(0\ 00012 \frac{1}{x})(0\ 05)} \theta_0 = 500 \times \theta_0 \text{ feet} \qquad (16)$$

where x is distance from station in miles and $\theta_0$ is reference heading in radians

It may be more convenient to have the residual error expressed in angular units Thus, for the typical parameters which have been assumed, the angular residual error is given by

$$\theta_\epsilon = 0\ 095\ \theta_0 \qquad (17)$$

For example, with a 20° reference heading angle $\theta_0$, there will be a residual displacement error in flying the omnirange course of 1 9° If the error cannot be tolerated, it may be removed either manually, by resetting the reference heading, or automatically by means of the low-speed integrator

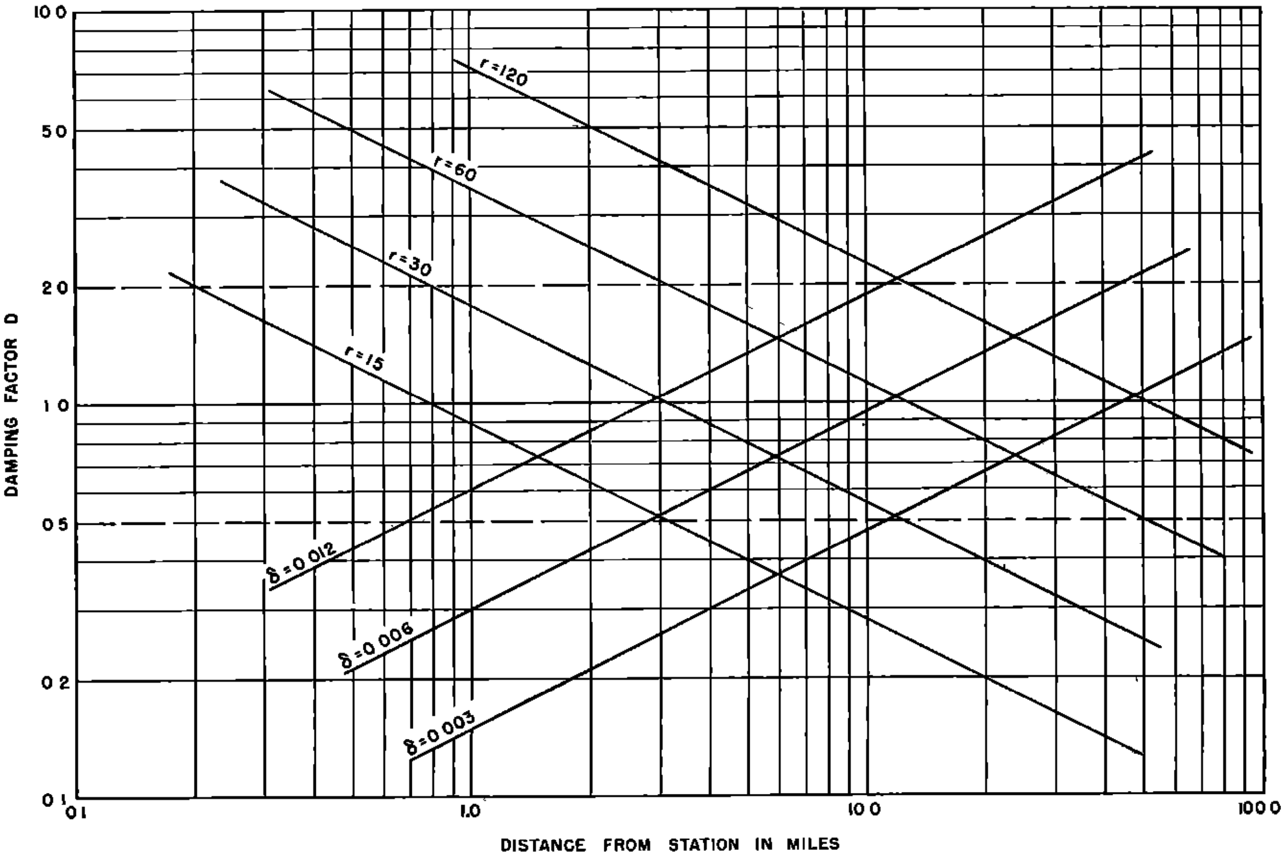



Fig 22 Omnirange Azimuth Control, Damping Factor Obtained with Various Values of Rate and Gyro Parameters, Used Separately

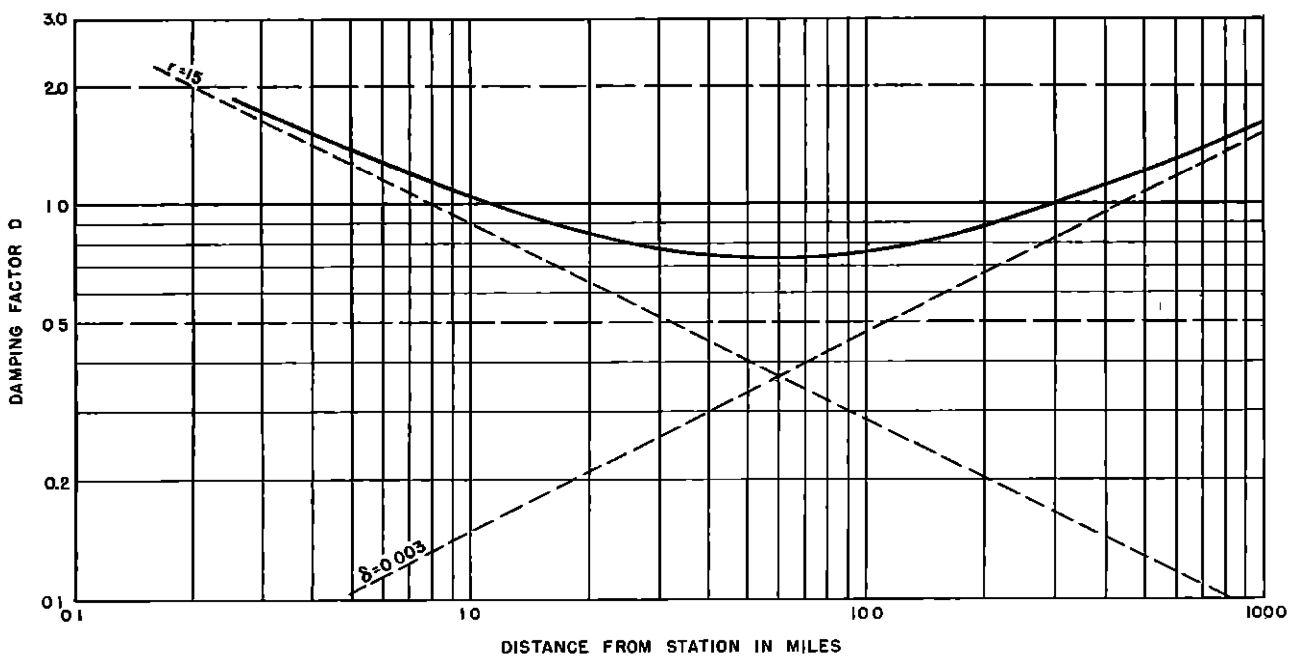



Fig. 23 Omnirange Azimuth Control, Combined Damping Factor