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PERIPHERAL VISION DISPLAYS

PHASE II REPORT

by Leroy L. Vallerie

Prepared by
DUNLAP AND ASSOCIATES, INC.
Darien, Conn.
for Electronics Research Center

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ABSTRACT

A laboratory study was conducted to determine the relative effectiveness of various concepts for the display of information in the periphery. Two commercially available display systems were investigated in conjunction with other concepts involving the use of flicker to encode airspeed signals and differential brightness to enhance the discriminability of input signals. Displays were designed to present tracking information in three control dimensions; viz., pitch, roll and airspeed. An adaptive loop simulator was employed to evaluate operator performance. The results of the study clearly indicated that effective control can be exercised using peripheral displays employing changes in motion as the primary encoding stimulus. A higher level of performance was achieved with one system which contained a single display for presenting integrated pitch and roll signals. The addition of airspeed was found to degrade performance in pitch and roll under all display conditions. Performance could not be enhanced by means of differential brightness. Further evidence was provided for the use of motion as a very effective means for encoding displays designed for viewing in the periphery.

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INTRODUCTION

Advances in our aerospacecraft capabilities have required man to perform an increasing number of complex, continuous control tasks based on visual information presented at the center of his field of view. A point is reached, however, in designing displays for such tasks where it becomes both impractical and inefficient to present all relevant information artificially on a single central display, or to supplement direct visual contact with superimposed symbolic data, such as is provided in certain aircraft projective systems; e.g., "heads-up" or weapon control displays. Many centrally located visual displays are also so heavily cluttered with symbols that they are difficult to interpret. For these reasons and others, designers have found it necessary to provide additional displays of redundant or supplementary information. These also have to be viewed with central vision so that man must switch his gaze rapidly between them and the primary information source. Time required to move and refocus the eyes in switching visually between multiple sources seriously restricts the rate with which man can acquire needed information. (Majendie, 1960; Wulfeck, Weisz, and Raben, 1958; Travis, 1948). This can have serious detrimental effects on performance, especially during difficult control tasks such as landing high-speed aircraft, operating airborne weapon control and detection systems while flying at supersonic speeds, or maneuvering and rendezvousing spacecraft using multi-dimensional control systems. Majendie (1960), for example, pointed out that conventional instruments consistently failed to solve three problems:

"(a) The difficulty of transition from instrument to visual flight conditions at the final stages of an instrument approach to land in bad weather."

"(b) The preservation of instrument control when the pilot's attention is, for any reason, directed away from the appropriate instruments. Preoccupation with other duties, lack of concentration due to fatigue, keeping a look-out for other aircraft, &c., are examples of situations when the maintenance of accurate flight control may be lost."

"(c) The effective monitoring of the accuracy and precision with which an automatic pilot is achieving its selected function. Admittedly, this can be achieved by the pilot continuously watching his appropriate primary instruments, but this tends to be extremely monotonous, and to a considerable extent reduces the advantages to be derived from effective automatic control. This particular problem reaches its peak under high altitude, high-speed conditions of cruise of a jet transport, and in the final stages of an automatic approach, automatic flare, or automatic landing, on any type of aircraft."

Majendie proposed to use peripheral vision displays to "provide flight intelligence to the pilot without distracting his attention from other tasks, without preventing him from looking freely about, either through the windscreen or within the cockpit, so that he can take appropriate corrective action from the information provided without serious interruption to his other tasks." He objected to the use of projective systems ("heads-up" displays) for the following reasons:

- "Of little use during maneuvering or turbulent flight.
- Unusable when the pilot's line of sight is more than about eight degrees from the projective display, e.g., under transition conditions in the presence of lateral displacement or wind drift.
- Unusable when the pilot's attention is within the cockpit.
- Indications of malfunction not inherently available, except to an attentive pilot."

In a similar vein, Fish (1950) also felt that "heads-up" displays were of limited use and might give rise to problems of double images. Double images do, in fact, exist in such displays and have created problems which are only now being studied and understood by researchers in the field.

Many studies provide evidence that man possesses a limited capacity for processing information, (Miller, 1956; Quastler, 1956; Broadbent, 1957; Welford, 1960; Fitts, 1964) and that human time lags resulting from visual switching and attention switching between information sources are major factors limiting the rate with which man can process information (Olson, 1963; Senders, 1965; Kristofferson, 1965; Broadbent, 1957; Broadbent, 1958; Broadbent, 1961). Other studies also indicate that man cannot attend to both central and peripheral sources of information simultaneously (Webster and Haselrud, 1964; Vallerie, 1967). Consequently, the peripheral retina should be treated as if it were a separate sensory input channel. Simply providing redundant information through the periphery, therefore, would not improve performance unless time lags due to switching could be reduced by this means.

Both simulator and flight tests have indicated that valuable tracking information can be obtained through peripheral vision "while" central vision is used to scan other information sources in the immediate environment and/or in the external environment; e.g., looking for the runway and, at the same time, attempting to scan cockpit instruments to obtain needed tracking information (Majendie, 1960; Chorley, 1961; Fenwick, 1963; Brown, Holmquist and Woodhouse, 1961; Keston, Doxtades and Massa, 1964; Holden, 1964; Moss, 1964a; Moss, 1964b). In these circumstances, the operator is required to switch only his attention to information presented in his periphery instead of spending time in redirecting and refocusing his eyes on spatially separated conventional displays. If visual switching were not a critical factor in such control tasks, no benefit would be expected to accrue from the use of peripheral displays.

During Phase I of this research program, a laboratory study was conducted to determine the effectiveness of peripheral vision displays for presenting dynamic tracking information during a difficult control task. It was hypothesized that the utility of peripheral displays may be attributed to a reduction in the time lost in visually switching between information sources. The hypothesis was tested by comparing the performance on a two-dimensional compensatory tracking task under conditions in which the requirements for visual switching and the provisions of peripheral displays were systematically varied and controlled. The study clearly demonstrated that tracking performance deteriorates as visual switching increases and that peripheral displays can be used to overcome its adverse effects.

Having demonstrated the feasibility of peripheral displays, the objective of this phase of the research program (Phase II) is to maximize their effectiveness and to develop general guidelines for their fabrication. To accomplish this objective, display concepts were selected for investigation in accordance with the known capacities of peripheral vision; the state-of-the-art in display techniques, and the constraints imposed by anticipated operational environments. Concepts not readily implemented in aircraft cockpits or space vehicles were not given serious consideration while concepts already developed and/or deemed operationally feasible were selected for investigation. The relative merits of the selected concepts were, then, measured using operator performance as the criterion for comparison and evaluation. This was accomplished in the laboratory under controlled experimental conditions during a simulated aircraft control task. Final evaluation of the most promising designs, of course, can only be accomplished under the more realistic conditions provided by high fidelity simulators and actual vehicles. This is the goal of Phase III of the program.

PSYCHO-PHYSIOLOGY OF PERIPHERAL VISION

A review of the literature dealing with the psycho-physiology of peripheral vision resulted in two basic correlative conclusions which are important in the design and evaluation of peripheral vision displays. These are:

- Visual sensitivity, generally, decreases with displacement from the fovea as would be expected based on the fact that the density of receptors decreases out into the periphery of the retina.

- Despite reductions in sensitivity, many visual functions persist in the periphery, especially brightness and motion discrimination which are, presumably, due to summation.

The first conclusion suggests one critical factor that must be considered in the design of peripheral displays. Regardless of the stimulus dimension under consideration, the range and the number of discriminable intervals within this range cannot be the same as those normally employed in conventional displays designed for foveal viewing. Therefore, peripheral displays will have to be designed expressly for peripheral viewing.

The second conclusion relates the class of stimuli most adaptable for use in peripheral displays. Motion and brightness change, or flicker are especially pertinent here, because they can provide continuous tracking information in the form of variations in direction and rate. Their relative merits, however, must be determined on the basis of their information transfer capacity in the context of a complex control task and on the basis of their operational feasibility. A differential brightness display, for example, might prove to be satisfactory only under relatively low or moderate levels of ambient illumination while a velocity display involving motion is satisfactory under a wide range of illumination.

STATE-OF-THE-ART

Until 1958, little attention had been given to the development of peripheral vision displays for the purposes of presenting dynamic control information. The earliest work, specifically devoted to these problems, was apparently carried out in England by Majendie, and later by Chorley and Lowe at Smith Industries, Ltd. The results of their efforts was the Para-Visual Director (PVD) shown in Figures 1 and 3.

Para-Visual Director (PVD)

The Para-Visual Director consists of three "barber pole" type displays located: one in front and the other two on either side of the pilot; all three in a horizontal plane below the line of sight. Each display consists of a servo cylinder with a black and white helix inscribed on its surface as illustrated in Figure 1. Rotation of the cylinder creates the illusion of longitudinal motion along its axis. The display in front of the pilot provides bank angle information while the other two side displays, slaved together, provide pitch. When the bank display shows motion to the right, the pilot banks to the right until motion ceases. When the pitch displays show forward motion, the pilot pushes his control column forward until motion ceases.

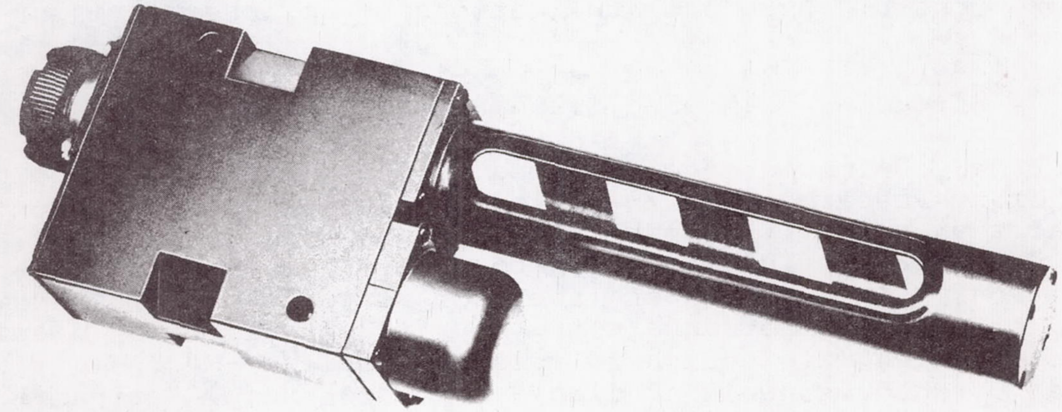


Figure 1. Smith PVD--Typical Display Unit

Majendie (1960) states "considerable flight experience with a wide cross-section of pilots has shown that this type of display is as nearly instinctively natural as one could possibly hope for." The display unit is also provided with integral lighting and a shutter which closes when malfunctions occur or when power is "off." The relationship between display speed and attitude demand is non-linear and a rate limiting signal is employed in the fully developed system. Subject to this, the system has been used for all phases of flight in which a conventional flight director would normally be used. KLM, for example, found that the PVD could be successfully employed to provide the pilot of a large jet aircraft (DC-8) with final approach and flare-out guidance (Reede, 1965). The PVD was driven by a flare-out computer.

Hopkin, at the Institute of Aviation Medicine, in Farnborough, was also concerned with the development of peripheral vision displays for aircraft use, but did not possess the same enthusiasm as Majendie. Hopkin (1959) completed a review of the literature dealing with peripheral vision and its relation to the design of peripheral vision displays, concluding: "Attempts to use other visual methods besides peripheral vision to convey additional information to the pilot have met with little success. The use of peripheral vision instead of scanning inside the cockpit is most unpromising." He also recommended that considerable caution be used in the application of peripheral vision because of the lack of definite knowledge about it and its liability to spells of very poor acuity. Hopkin emphasized the need "a) to measure peripheral vision adequately; b) to find out what the capabilities of peripheral vision are; c) to discover methods of improving peripheral vision performance; and d) to explore possible uses and applications of peripheral vision."

Streaming Light and Flashing Light Displays

Brown, Holmquist and Woodhouse (1961), at the Applied Psychology Research Unit in England, were interested in peripheral vision and its capabilities for presenting information to pilots during final approach to landing under poor visibility conditions. In a series of laboratory experiments, they compared tracking performance using four flight-direction displays, three of which were peripheral vision displays--Majendie's Para-Visual Director as well as displays consisting of "streaming lights" and "flashing lights." The fourth instrument was a conventional ILS indicator.

The streaming light display system consisted of two 53.34 cm rows of 45 neon lamps, spaced at equal intervals. One row was oriented horizontally at a visual angle of 25 degrees below a central display. This row was used to indicate errors in heading. The second row, oriented vertically at a visual angle of 30 degrees to the left or right of the central display, was used to provide altitude error. Eight lamps in each row were illuminated at any instant to produce an apparent streaming movement of lamps. The direction of the streaming movement indicated the size of required movement. The tracking task, here, as well as with the other displays studied, was compensatory with zero time lag.

The flashing light display system consisted of four neon lamps. Two lamps, displaying errors in altitude, were placed 25 degrees vertically above and below the central display. The other two lamps were placed horizontally to the left and right of the central display, at a visual angle of 30 degrees. A flashing light to the left indicated a requirement for movement to the left and a flashing light above indicated a movement towards the operator of an aircraft type control. The rate of flashing indicated the size of the control movement required. When the system was balanced, the lamps were off. The flashing light system was also studied with the lights attached directly to the visor of the operator's helmet.

The Para-Visual Director (barber's pole) system used in these experiments was described earlier. Here, the central display presented changes in bearing and the two side displays presented changes in altitude even though they were mounted horizontally. In one case, only one (right) display was used.

The ILS meter was located at the right and slightly above the center display at a visual angle of six degrees. The horizontal pointer displayed altitude and the vertical pointer bearing. When the horizontal pointer moved up the correct control movement was towards the operator. When the vertical pointer moved left, the required control movement was to the left. The target area on the meter was represented by a white circle (7.95 cm in diameter). Tracking with the ILS meter was also examined when it was located ten degrees directly below the central display.

All displays were attached to a 76.2 cm diameter hemisphere at the displacement angles indicated above. The central display consisted of a 15.24 cm diameter ground glass screen located at the center of the curved surface of the hemisphere. Three spots of light were projected on the screen in a pre-arranged order. (A second "central display,: 70 degrees to the right of the center of the hemisphere, was used in the portion of the experiment dealing with the effects of head rotation and of combining two display systems.) The operators basic tasks were to fixate the central display, to press a switch as quickly as possible whenever the pattern of spots changed, and to track at the same time with the flight-director display system.

The results of the study indicated that during "continuous tracking, the time off target with Flashing Lights or the ILS meter was about a quarter of the time off target with either the Streaming Lights or the Barber's Poles. In correcting sudden errors, Flashing Lights on the Helmet gave quicker responses than any other display which was investigated. This was presumed to be the result of the high attention-getting value and the immediate directional indication of the signals. The weakness of Flashing Lights on the Helmet, which also applied to the Barber's Poles and Streaming Lights, was presenting information on the size of errors. The ILS meter was the best display in this respect, although it did not always attract the man's attention as soon as it indicated an error. The combination of Flashing Lights on the Helmet and the ILS meter produced the quickest corrections recorded during the experiments.

"Reaction time to signals presented on a central display increased about 40% when attention had to be paid to any of the flight-director displays. The size of the increase was about the same whether simulated control of the aircraft was carried out or not while performing the central task." They concluded that: "It was the need to attend to the additional channel of information, rather than simultaneous demands for action, which interfered with the central task.

Performance with Flashing Lights on the Helmet and Streaming Lights showed only a small and not statistically significant adverse effect from occasional rotation of the head and eyes of 70 degrees.

"Sideways movement of the head altered the angle subtended at the subject's eye by the Barber's Poles mounted horizontally fore and aft to display information on altitude. This changed the apparent rate of movement of the display and the apparent display-to-control ratio, and thus caused the subject to miss small errors occasionally, or make control movements of the wrong size. In addition, with the Barber's Poles the display-control directional relationships changed as attention was directed from one end of the azimuth display to the other. This could occur in an aircraft when the pilot rotated his head and eyes, and might be dangerous." This last conclusion made by the authors is inconsistent with the normal interpretation of display-control relationships in that they have interpreted the area of intersection of two displays as an additional source of information to which the operator can attend in addition to the two basic input sources comprising it. If such confusion was a real problem, physical separation of the two displays and/or training should minimize this effect.

Peripheral Command Indicator (PCI)

In the United States, Collins Radio Corporation, as early as 1961, was also interested in the possibility of using peripheral vision displays in the aircraft cockpit, and developed the "Peripheral Vision Command Indicator" as shown in Figure 2 (Fenwick, 1963), against a background of actual flying experience and laboratory simulation. This development effort was undertaken because of increased pressures for lower aircraft landing minimums under adverse weather conditions.

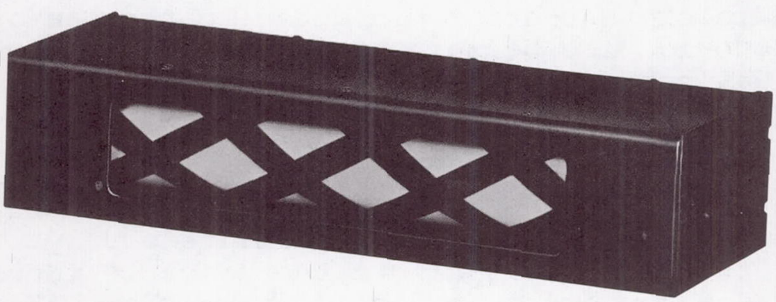


Figure 2. Collins' peripheral command indicator

Collins' peripheral command indicator translates pitch and bank steering information into a rate of movement of a single, black and white moire pattern. With appropriate inputs to the device, which consists of a helix on each of two concentric cylinders, the black and white pattern moves in any desired direction (up, down, left, right, and any vector between these) at any desired rate within a wide range. In practice, movement of the pattern has been controlled by quickened flight director signals so that the display presents the pilot with a continuous, two-dimensional, compensatory tracking task. Fly-to-sensing is employed so that, for example, if movement is perceived in the direction 15 degrees to the right of vertical, the pilot pitches up and steers slightly to the right until the display is nulled; that is, until movement ceases. The rate of movement represents the magnitude of error to be corrected (Fenwick, 1963).

Early tests with the instrument indicated that sensitive commands in two axes could be perceived and followed even when the pilot was attending to other instruments in the cockpit or scanning the windscreen. Simulator tests were used to determine the usefulness of the peripheral command indicator as a supplement to conventional displays. Laboratory experiments were also conducted to assess the "effects and interactions" of various display variables in an effort to optimize the display. With the best combination of display variables, Fenwick (1963) states that "direction of motion could be perceived with considerable accuracy when the display was located as far as 35 degrees from the subject's line of regard."

A rather unique location for the PCI was used by Knemeyer (1966), who was also concerned with the alleviation of transition problems associated with low visibility landing. The PCI was vertically mounted on the nose of an aircraft, outside the cockpit at a distance of approximately nine feet directly in front of the pilot. Two electro-luminescent columns and a reference line were added to present errors in speed so that an optimum angle of attack could also be maintained on final approach. Approach speed was correct when the columns were centered on the reference line. Speed was too high or low when the columns were above or below the line, respectively. The intersecting lines of the display were driven by the output of a flight director computer. The pilot, therefore, received continuous command information on pitch, roll, and speed, simultaneously. Knemeyer (1966) states, "the instrument allows the pilot to focus on his visual reference on the ground and still have his most important flight information easily available to him without having to focus his eyes inside the cockpit on his instrument panel. The instrument is narrower than the distance between his eyes, so that nothing will be obstructed in the pilot's field of outside visual reference. The flight information is so dominantly presented that the pilot will perceive it even when he intensely focuses on his visual references on the runway. Extensive preliminary flight evaluation has been performed during visual day and night approaches and landings. Numerous touchdown landings have been made using the flare indication which this instrument can provide when driven by the flight director computer. The tests have shown that such an externally mounted flight command indicator solves the main safety problem in low visibility landing by giving the pilot continuous control information easily accessible to him while remaining on visual contact and after transitioning to outside reference when breaking out from instrument flight."

Peripheral Artificial Horizon Display

Keston, Doxtades, and Massa (1964), at the Laboratory for Electronics, were concerned with the possibility of using a peripheral artificial horizon as an aid to pilots during night carrier landings. They conducted a laboratory study to determine the feasibility of using such an aid. The artificial horizon consisted of a thin luminous line presented in a horizontal plane at eye level; the central ten degree visual angle of which was removed resulting in a "peripheral" display. The operator's task was to judge the vertical position with respect to his line of sight. No central tracking or loading task was used. The authors reported a "dramatic" enhancement of reliability and accuracy" with the use of the artificial horizon. Variability and errors were reported to be far greater when no horizon was present in the periphery.

Differential Brightness vs. Positional Displays

Moss (1964a, b) compared tracking performances using a positional display and a differential brightness display as they were moved into the periphery (15 degrees, 30 degrees, and 45 degrees eccentricity.) Performance with the positional display was superior when it was situated in the center of the field of view. However, as the displays were moved into the periphery, the differential brightness display proved to be the better of the two. These results emphasize the importance of selecting the appropriate stimulus dimensions for use in the design of displays for peripheral viewing.

Horizontal Side Bar Display

Holden (1964) at the Queens University in Belfast, Ireland, investigated the use of horizon "side bars" to create the illusion of a stationary horizon in the pilot's periphery during blind flying. The side bar display system consisted of two instruments in the periphery. A horizontal line on each instrument moved up or down as the aircraft banked. In 1963, Holden conducted a simulator study of this system. The side bars were located to form a plane about a foot below the line of sight on either side of the head. The side bars were geared so that they formed an extension of a central artificial horizon display which was situated directly in front of the pilot. The results of the study indicated that small changes in bank angle were detected more quickly with the use of side bars; however, even with modifications, the illusion of a stationary horizon was not achieved. Nevertheless, a 22% improvement was found with the side bars in tests which required the pilot to track in roll and pitch simultaneously. Here, the bars were modified to move "in sympathy" with aircraft pitch. Holden concluded that the major advantage of the side bar system appears to be in its ability to reduce the amount of concentration required of the pilot.

In discussing other instruments for blind flying, Holden stated that "director instruments (integrated displays) can become exceedingly complex...and such a complex instrument may offer only marginal advantages over the conventional display." With regard to Majendie's Para-Visual Director, he also pointed out that "in any case reliance, in a primary instrument, on peripheral vision is open to severe criticism since medical evidence indicates that it would be quite easy to miss peripheral clues at a crucial stage when under strain. Relegated to a secondary instrument the system still appears to have many merits, the pilot flying the aircraft with normal instruments using the PVD display to help ease the task by reducing the concentration required."

Minimum Attention Display

In the 1964 summer issue of the Journal of the Institute of Navigation, and again in the 1965 summer issue of the same journal, Massa and Keston revealed a "new display concept--The Minimum Attention Display." Keston (1964) states: "The Minimum Attention Display Concept attempts to provide highly specific and veridical guidance information that would augment and clarify direct visual contact through visual codes compatible with the required control responses. The display has minimum attention requirements; that is, it does not compete for the attention of the pilot to the detriment of both the display and direct visual contact. The pilot is not required to look directly at the display; instead, he can look through the windscreen and maintain direct visual contact. This is usually accomplished by transmitting information through the visual periphery by means of non-specific (low-acuity) visual parameters (color, motion, flash range, brightness, etc.)

"The use of this unique display concept allows continuous maintenance of direct visual contact, while simultaneously providing supplemental guidance information. The time scale required for information transmission is thus compressed, resulting in more rapid performance of critical control maneuvers.

"The Minimum Attention Display Concept is proposed as one form of solution to several display problems (delineated above) inherent in both manual and automatic systems."

Massa and Keston (1965) wrote: "We conclude that a distinct possibility exists for the utilization of peripheral phenomena in information transmission in a minimum attention visual display." They considered the following stimulus dimensions to be the most promising: "flicker frequency, color discrimination, relative size discrimination, relative position discrimination, relative velocity discrimination, relative shape discrimination."

DISPLAY CONCEPTS

During Phase II of this research program, a number of display concepts appeared worthy of further investigation in the laboratory. Among these were the Collins Peripheral Command Indicator (PCI) and the Smith Para-Visual Director. These are the only two display systems which are presently in operational use and are commercially available as off-the-shelf items. Both displays incorporate changes in motion as the primary stimulus for encoding information on direction (pitch and roll) and rate. Display concepts incorporating other than changes in motion as the primary dimensions were not given serious consideration because of their relatively limited discriminability in the periphery or their incompatibility with anticipated operational environments. For example, the effectiveness of displays utilizing color, brightness, and flicker rate would be influenced by the level of ambient illumination on the cockpits of aircraft and space vehicles. Displays requiring shape and pattern recognition would suffer more from accelerative forces than those providing motion or brightness cues. Other factors, which were also considered, included the availability of space for mounting, structural shape of the operator's workspace, power conservation, and weight. In addition, displays which rely on their spatial positioning in the operator's visual field to convey information were also not considered promising since four instruments would be required to present information on two control dimensions; viz., two pairs of displays would be required to present direction and rate information, one above and one below the operator's line of sight for "upness" or "downness" and a second pair on either side of the operator for "leftness" or "rightness." A single peripheral display, capable of providing this same information with no deleterious effects on control performance, was considered to be more desirable than a multi-display configuration.

Motion cues were also considered most promising because they can provide quickened tracking information; viz., a conventional display in the center of the visual field for presenting positional information (error) and the peripheral display(s) for presenting a combination of error and error rate (or higher derivatives depending on the dynamics of the system controlled).

Flicker displays could also be used in this manner; however, they may suffer from the same limitations as found with streaming light displays (Chorley, 1961), i.e., they may distract and annoy the operator even though they can provide useful control information. Displays incorporating changes in brightness or size could not be effectively used to provide quickened information. In addition, display concepts utilizing other than motion as the predominant stimulus dimension must also depend on their location in the operator's visual field for directional cues which require an undesirable multi-display configuration as explained previously. This limitation, of course, does not preclude the use of flicker, brightness or other stimuli to enhance the signal value of motion displays. For example, brightness might be used to present redundant information, i.e., the background brightness of the motion display might increase to bring the operator's attention to gross tracking errors requiring immediate action.

Brightness, flicker or other stimuli might also be used to enrich the information content of a motion display by providing supplementary information such as airspeed, radar range or rate of descent. In this way, information on a third tracking dimension might be simultaneously presented to the operator. Enriched displays may, of course, also be enhanced. For example, changes in the rate of motion would be utilized to present pitch and roll information; gross errors would be indicated by an increase in the rate of display motion as well as an increase in the overall intensity of the display background; and deviations from a present optimum airspeed would be presented by a slow flicker meaning "too slow" and a fast flicker meaning "too fast." Here, the operator's task would be to adjust his controls so that no apparent motion or flicker could be perceived peripherally. His attention would be immediately directed to gross errors by an increase in the rate of motion as well as an increase in the background brightness or the display.

In view of the above discussion, it appeared desirable to investigate the following display concepts during the Phase II experimental program.

Para-Visual Director (PVD)

Conventional PVD's were studied as supplied by their manufacturer and in accordance with their recommendations. The three displays were located in the operator's visual field as illustrated in Figure 3. The center display presented roll information and the two side displays pitch. The control-display relationship was inside-out; i.e., apparent movement to the left on the center display indicated a requirement to move

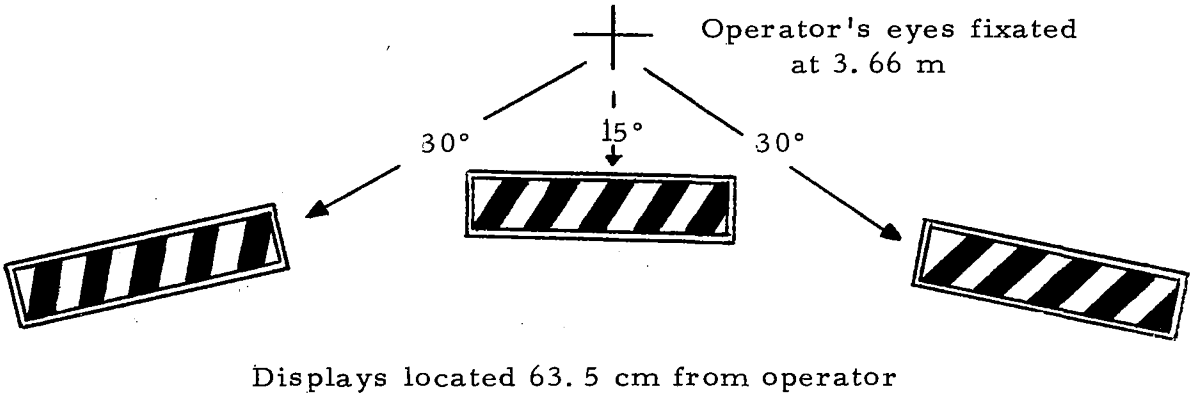


Figure 3. Location of PVD's in Visual Field

the control to the left; forward movement on the two side displays indicated a requirement to push the stick forward; movement perceived in opposite directions, of course, required reverse control movements. The rate of motion indicated the amount of correction required to null the display and to attain zero error.

Peripheral Command Indicator (PCI)

The PCI is a single display containing a moire pattern of intersecting lines. By translating the two sets of lines across the display surface at different relative speeds, it is possible to produce the appearance of motion in many directions; i.e., up, down, left, right, and any direction between these vectors. The PCI was used as recommended by its manufacturer and located in front of the operator, 15 degrees below his line of sight.

Concept of Enrichment

Enrichment refers to the addition of supplementary tracking information in the periphery such as airspeed which the operator would normally be forced to obtain from conventional displays designed for foveal viewing. During this study, airspeed information was presented by flickering the background brightness of the PCI and the central PVD display. Low airspeed was indicated by a flicker rate of 2hz and high airspeed by a rate of 4hz. The operator's task, therefore, was to control three tracking dimensions simultaneously (e.g., pitch, roll, and airspeed) using information presented entirely in his periphery.

Concept of Enhancement

In contrast to enrichment, where additional stimulus dimensions are used to provide supplementary information, enhancement refers to the use of additional dimensions (e.g., flicker or brightness changes) to provide redundant information in an effort to improve the discriminability of input signals. For enhancement to be effective, the primary encoding technique (e.g., changes in the rate of motion) must be less than adequate for conveying the information required by the operator to control the vehicle properly. Because of the perceptual limitations of the periphery, enhanced displays may be the only type which can be used to convey all the information required by the operator for efficient control of a vehicle. The effects of enhancement on performance, therefore, was of primary interest. During this study, PVD and PCI displays were enhanced by increasing their background brightness to bring the operator's attention to gross errors (>±50%) requiring immediate correction.

METHOD

Display concepts were tested and compared on the basis of operator performance during a simulated aircraft control task. The task involved the correction of errors in pitch (x) and roll (y) by means of compensatory tracking using a pressure stick hand control. Under some conditions, errors in airspeed (z) were also presented to the operator using flicker as the encoding dimension. Airspeed was controlled with a hand throttle. Peripheral displays for presenting pitch, roll, and airspeed were located at a distance of 25 inches (63.5 cm) around the operator's head in accordance with the scheme illustrated in Figure 3. A head and chin rest was employed to stabilize the displays in the operator's field of view. A fixation point was situated at a distance of twelve feet (3.66m) from the operator's eyes. Operators were instructed to fixate this point and not to "look" at the peripheral displays.

The difficulty level of the control task and performance scoring was accomplished by using a new and rather unique technique developed by Kelly (1962). This technique involved the use of self-adjusting loops in the control circuits of the simulator. Conventionally, a variable score is employed to represent the operator's performance in a task of fixed difficulty. In this case, a score representing the desired performance (error tolerance) was fixed and the difficulty of the task varied automatically as a function of the operator's performance to produce the fixed performance score. The average difficulty of the task achieved within a fixed time interval of fifteen minutes was the performance index for comparing the various display concepts.

A block diagram of the simulator is shown in Figure 4. Detailed circuit diagrams are presented in Figures A-1, A-2, A-3, A-4, A-5 and A-6 of the Appendix. Equations of motion were programmed on an analog computer to provide second-order dynamics for the control task. The second derivative of the simulator output was obtained by summing the outputs of the pressure stick and a disturbance function generator for the pitch and roll channels of the control task.

The disturbance function generators were programmed to produce acceleration errors via an adaptive loop in each control channel. Each generator consisted of three independent sine-wave oscillators. The frequencies of oscillation (see Appendix) were selected to generate a random waveform whose period was long enough to prevent the operator from memorizing or anticipating the control task inputs. The amplitude of the summed frequencies from the oscillators were controlled by the adaptive loop.

The operator's task was to null the input errors using the pressure stick control. As the error in either pitch or roll was decreased and approached zero, the adaptive loop caused an increase in the output of the disturbance function generator and a greater error to be displayed to the operator. The adaptive loop equation for all control channels was of the form:

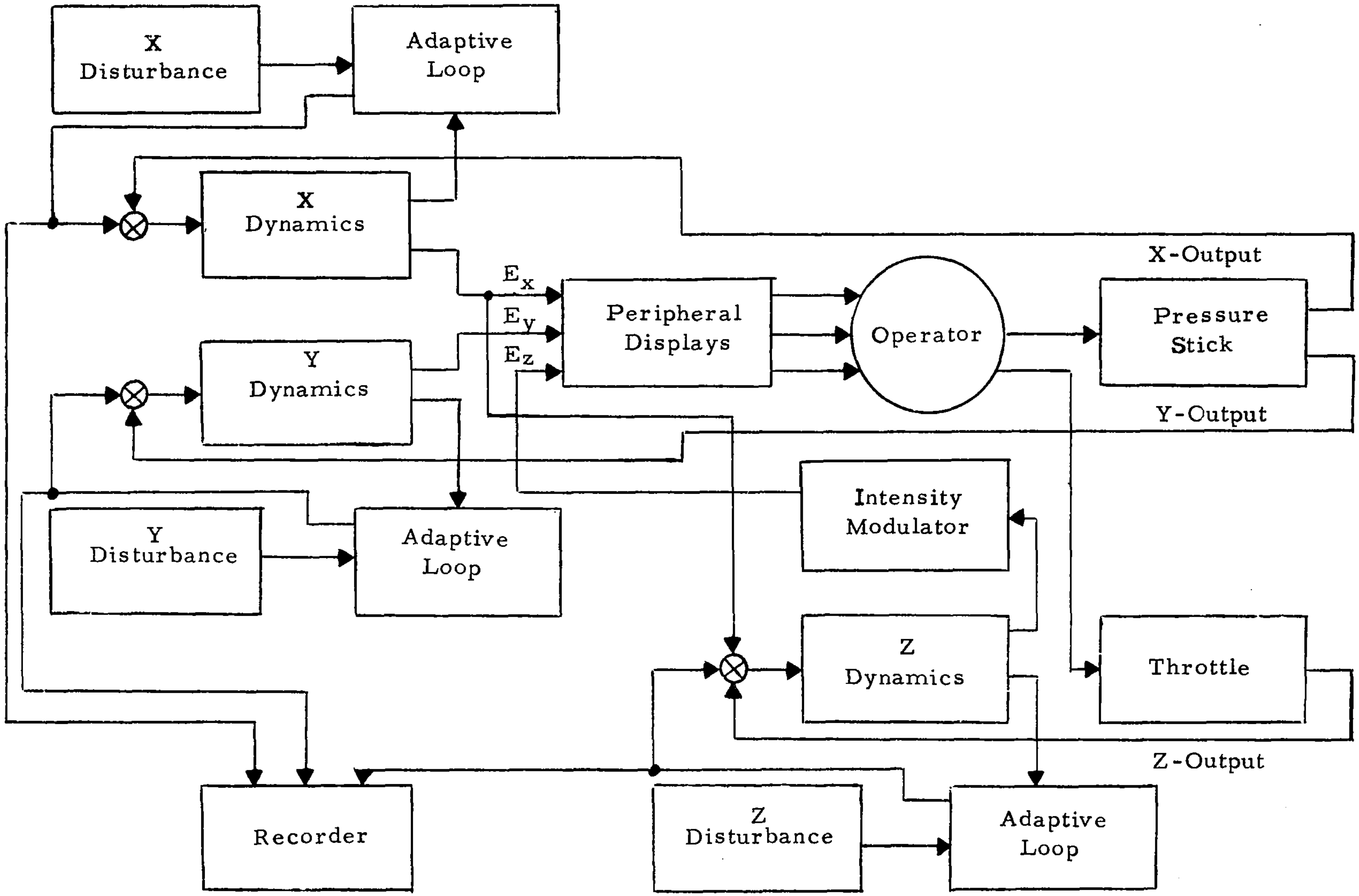
$$C = K \int_0^T (e_L - |E|)\,dt + C_{initial}$$

C = the percent of disturbance, a higher value denoting better performance

e_L = the "error threshold" or error criterion the task is to meet

E = the absolute error

K = a coefficient governing the rate of increase or decrease of C



Pitch (X)
Roll (Y)
Airspeed (Z)

Figure 4. Block Diagram of the Simulator

Whenever the error was less than criterion, system difficulty increased. When error was greater than criterion, however, system difficulty decreased and the system became easier. Thus the system was adjusted to the difficulty level that produced e_L units of error, and oscillated around that value. The actual equation used was:

$$C = .014 \int_0^{15\text{ min.}} (.33 - |E|)dt + 0$$

$C_{initial}$ was set at zero at the beginning at each trial; i.e., the operator started with no disturbance. The loop then began to open and continued to open until the operator achieved a difficulty level which he could control at the preset error threshold (e_L). A low value of K was employed in the adaptive loop to prevent the system from oscillating in an uncontrolled fashion.

The system was designed so that large errors in pitch (> ± 10%) would also affect airspeed; viz., airpseed increased or decreased with excessive "nose down" or "nose up" excursions, respectively. Except for the influence of pitch on airspeed, the same adaptive loop technique was employed in the airspeed channel. Two comparators, driving relays, and an intensity modulator were used to flicker the background brightness of the peripheral displays when airspeed was outside of tolerances preset at ±10%. Flicker rates were 2hz when airspeed was too low, and 4hz when it was too high. A steady intensity indicated that airspeed was being maintained within tolerances.

Under other conditions, the peripheral displays were enhanced by increasing their background brightness in order to alert the operator of excessive errors (> ± 50%) in either pitch or roll. This should not be confused with enrichment, discussed above, which involved the presentation of supplementary information such as airpseed. A comparator was used to operate a relay when the preset error tolerances were reached in either the pitch or roll channels. The relay caused the background intensity to increase to a level of 1.0 FL. The normal operating intensity was fixed at 0.2 FL for all displays.

A multi-channel recorder was used to record the output "C" from each of the adaptive loops. This output is an index of the task difficulty level achieved by the operator while he controlled the simulator. A high score, therefore, indicates that a large amount of disturbance could be maintained within the fixed performance tolerances. Display configurations which yielded high scores were judged better than those which yielded low scores.

The pressure stick hand control was Model 435DC, manufactured by Measurement Systems, Inc. A diagram of the pressure stick circuit is contained in Figure A-6 of the Appendix. The stick was situated directly in front of the operator and oriented vertically for use with the right hand. The control-display relationship was arranged in an "inside-out" configuration; the operator moved the stick in the direction of movement in order to null the errors in pitch and roll. The throttle control was situated for convenient use with the left hand. Forward movement of the throttle increased airspeed.

The experimental room was dimly illuminated at a level of 0.2 FC. The area surrounding the displays was coated with flat black paint which reflected an immeasurable amount of light. The background of the displays was set and maintained at 0.2 FL under normal (unenhanced and unenriched) conditions. The helices of the displays were essentially opaque to the eye.

A total of six display conditions were presented to each operator in a different random order. A "four dimensional" design was employed as illustrated in Table I. The "C" factor was included primarily to uncover any differential effects on pitch and roll performance due to the various display conditions.

A random order of presentation was employed in order to attenuate any undesirable effects due to learning, sequence, or uncontrolled variations in the experimental environment which might bias the results. Each operator received a total of two hours of practice with the various display configurations prior to his participation in the main experiment. Each practice session lasted for approximately twenty minutes. The operators, therefore, were familiar with the displays and used to the control-display relationship before participating in the experiment. Five minutes of practice was also given immediately prior to each experimental trial. Trials lasted for a period of 15 minutes.

Six subjects were provided by Dunlap and Associates, Inc., to serve as operators during the study. Their eyesight was tested and determined normal using standard tests of central and peripheral vision. Standard instructions were given to the operators. They contained an explanation of the overall purpose of the study, the control task, and the importance of maintaining the visual fixation point. The experimenter monitored the operator's eyes and noted any instances of "peeking" at the peripheral displays. No such instances were encountered during the study.

TABLE I
DESIGN OF EXPERIMENT

	DISPLAY CONDITIONS					
	PVD (A_1)			PCI (A_2)		
	Alone (B_1)	Enhancement (B_2)	Enrichment (B_3)	Alone (B_1)	Enhancement (B_2)	Enrichment (B_3)
SUBJECT (S)	C_x C_y N/A	C_x C_y N/A	C_x C_y C_z	C_x C_y N/A	C_x C_y N/A	C_x C_y C_z
1	6*	5	3	4	1	2
2	2	4	1	5	3	6
3	5	1	6	3	2	4
4	1	2	5	4	6	3
5	3	2	1	4	5	6
6	3	4	1	6	2	5

* Sequence of presentation

RESULTS AND DISCUSSION

Control performance, recorded during a typical trial, is shown in Figure 5. The graphs in the figure indicate the percent of disturbance ("C" in the adaptive loop equation) that was controlled within the preset error tolerances (e_L) for each control channel of the simulator. In this trial (No. 3), the operator (No. 4) was able to maintain control until the disturbance reached a level of 70% in roll, 40% in pitch, and 78% in airspeed. These levels were attained in approximately ten minutes; at which time, he could tolerate no further disturbance and still maintain control within specified limits. Performance recorded during the remaining trials took this same general form; i.e., a slow rise to an asymptote after approximately ten minutes. The performance index, employed to evaluate the various display concepts, was the highest level of disturbance achieved in each control channel during the last five minutes of the trial. This level was expressed, as in the above case, as a percent of maximum possible disturbance ($C_{max.}$). Other performance indices, of course, could have been used; however, this one appeared to be the most appropriate for the present purpose.

The primary results of the study are summarized in Table II. In general, a higher level of mean performance was achieved with the PCI than with the PVD regardless of the control channel and the display condition; i.e., either used alone, enhanced to improve the discriminability of input signals, or enriched by the addition of airspeed. An analysis of variance was performed to determine if the difference between displays was real or more likely due to chance fluctuation of the performance indices. The results of the analysis are shown in Table III. Using an F-Test, the analysis indicated that the obtained difference is significant at the five percent level and cannot be reasonably attributed to chance. A comparison was also made between the mean performances for the PVD and PCI under the "alone" condition without enhancement or enrichment; i.e., A_1 B_1 versus A_2 B_1. The difference between the two mean performance measures was twelve points, as shown in Table IV, favoring the PCI. The Studentized Range Test was employed and the difference found significant at the .01 level. Hence it again appears that there was a real difference between performance of the operators with the PVD and PCI. Based on the results of both tests, therefore, it can be concluded, with some degree of certitude, that operators in this experiment achieved a significantly higher level of performance with the PCI than with the PVD.

A number of possible explanations can be given for the difference found between the two displays. Among these, three explanations appear to be plausible, any one or combination of which could reasonably account for the observed differences.

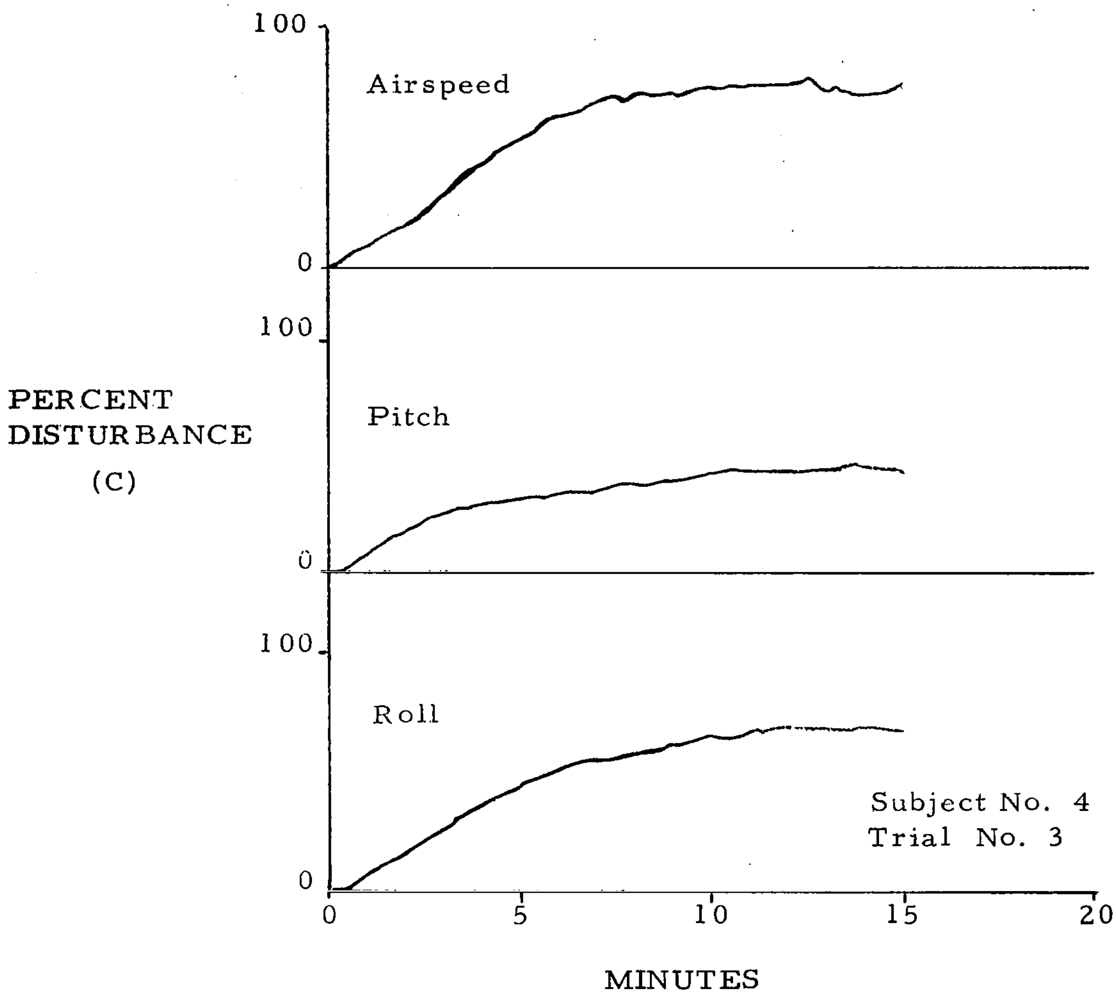


Figure 5. Typical Performance Recording

TABLE II. AVERAGE LEVEL OF DISTURBANCE ACHIEVED UNDER ALL CONDITIONS

DISPLAY CONDITIONS

RECORDER CHANNEL	Para-Visual Director A_1			Peripheral Command Indicator A_2		
	Alone B_1	Enhanced B_2	Enriched B_3	Alone B_1	Enhanced B_2	Enriched B_3
Pitch C_x	47	41	43	57	58	48
Roll C_y	55	55	49	69	66	58
Airspeed C_z	N/A	N/A	83	N/A	N/A	85
Pitch and Roll $\frac{C_x + C_y}{2}$	51	48	46	63	62	53

Note: Figures are the percent of disturbance achieved by all operators combined.

The first and most reasonable pertains to the workload placed on the operator. With the PVD, pitch signals are presented on two side displays and roll signals on a single display in front of the operator and below his line of sight. To null the errors presented in pitch and roll, he had to first determine an appropriate direction in which to move his control stick. This operation, of course, is performed very quickly and skillfully after some practice. Nevertheless, the separation of the two control dimensions in the visual field placed the task of integrating the two signals into a single and appropriate control movement on the operator. In the case of the PCI, the integration is performed very simply on the display itself so that the operator needs only to follow the presented vector with his control stick. No time is consumed or information processing capacity occupied by the integration function.

A second explanation involves the concept of attention switching. As discussed in the report on Phase I of this research program (Vallerie, 1967), there appears to be good evidence to indicate that man cannot attend to more than one part

TABLE III. SUMMARY OF ANALYSIS OF VARIANCE

Source	SS	DF	MS	F-Ratio
A	2167	1	2167	9.72*
B	717	2	359	3.21
C	1750	1	1750	12.41*
S	2110	5	422	——
AB	175	2	88	2.44
AC	3	1	3	.15
AS	1117	5	223	——
BC	36	2	18	.55
BS	1115	10	112	——
CS	707	5	141	——
ABC	108	2	54	3.38
ABS	358	10	36	——
ACS	99	5	20	——
BCS	328	10	33	——
ABCS	159	10	16	——
TOTAL	10,949	71		

*P = <.05

TABLE IV
DIFFERENCES BETWEEN PAIRS OF MEANS

DISPLAY CONDITION

DISPLAY CONDITION		A_1B_1	A_2B_2	A_2B_3
	A_2B_1	-12**	-1	-10*
	A_1B_2	-3		
	A_1B_3	-5^{+}		

* P = <.05 (Studentized Range Test)
** P = <.01 (Studentized Range Test)
\+ P = <.05 (T-Test using pooled high-order interactions)

of his visual field simultaneously; i.e., man cannot attend to both central and peripheral sources of information nor to two peripheral sources at the same instance of time. Some finite time is, therefore, required to switch attention from one source to another (Kristofferson, 1965). If this is true, time involved in switching attention from one display to another in the visual field would limit the rate with which the operator could process information. Such might be the case with the PVD. Since the PCI is a single display, this limitation on performance would not apply.

The third explanation concerns the perceptual limitations of the periphery. Discriminability of most stimulus dimensions, including motion, deteriorate as the distance from the fovea increases into the periphery. In the case of the PVD, pitch information was presented on two displays, located on either side of the operator at an eccentricity angle of 30 degrees. With the PCI, pitch information was presented in conjunction with roll information on a single display situated at an eccentricity angle of 15 degrees below the operators' line of sight. Since pitch information was situated at a greater eccentricity angle, in the case of the PVD, the discriminability of pitch signals would be expected to be worse as compared with the PCI. If this interpretation is correct, pitch performance should have been worse than roll in the case of the PVD but comparable to roll with the PCI. However, this was not the case since pitch was worse than roll for both displays and almost equally so under all experimental conditions as shown in Table II.

The results of the analysis of variance in Table III also indicated that the mean difference between pitch and roll was significant and, most probably, not due to chance fluctuation of the performance scores. The possibility that this difference could be due to a bias in one of the channels of the simulator has been ruled out after careful re-examination of simulator circuits and settings. It appears appropriate to conclude, therefore, that the operators found it more difficult to control pitch than to control roll under all experimental conditions regardless of which display was being utilized at the time.

The mean scores in Table II also indicate a degradation in performance with the addition of airspeed signals which were encoded in the form of flickering background illumination on the PCI and the central PVD. This effect, evidenced by the enriched condition shown in the table, appears to apply to both the PVD and PCI display systems. A Studentized Range Test was employed to test the differences between individual pairs of means. Specifically, mean performance obtained during condition A_1 B_1 (PVD used alone) was compared with A_1 B_3 (PVD enriched with airspeed) and A_2 B_1 (PCI used alone) with A_2 B_3 (PCI enriched with airspeed). The results of this test are summarized in Table IV. For the PCI, there was a reduction of ten points when airspeed signals were added to the display. This reduction in performance could not be reasonably attributed to chance. Therefore, the difference is considered real and significant. The reduction of five points in the case of the PVD, however, did not quite reach the 5% level, the a priori level selected for use in this test. Consequently, the difference could quite possibly be due to chance fluctuation of the obtained scores even though it is in the correct direction from a theoretical viewpoint. The less conservative T-Test using the pooled higher order interactions from the analysis of variance as the error term did, however, indicate that this difference was significant at the 5% level. Based on these tests, therefore, it can be concluded with some degree of certitude that the addition of airspeed signals did degrade performance with both displays. This conclusion conforms with other research (Miller, 1956; Quastler, 1956; Broadbent, 1957; Welford, 1959, 1960; Fitts,1964) which provide corroborative evidence that man possesses a limited capacity for processing information.

In this study, the operators did indeed control airspeed quite well but only at the expense of performance in pitch and roll. This finding would appear to provide further evidence for the hypothesis concerning limited channel capacity. Since the adaptive loop technique was employed, operators were not required to control the simulated vehicle at preset levels of difficulty, which may have been set far below their maximum capacity for information processing. Instead, the difficulty level was allowed to vary as a function of the operators' performance; the operators always attempting to achieve the highest possible score compatible with their own individual criterion level. Operators in this study were highly motivated and conscientiously strived to achieve a high score. For this reason, it can be stated that they were performing very close to their own capacity for information processing. The addition of airspeed, therefore, would be expected to add to their already high workload and interfere with those tasks involving the control of pitch and roll as evidenced by their performance scores.

In contrast to enrichment, where an additional stimulus dimension (changes in the rate of flicker) was used to provide airspeed information, enhancement refers to the use of an additional stimulus to provide redundant information in an effort to improve the discriminability of input signals. As shown in Table II, performance with neither the PVD nor the PCI were improved by enhancing them with changes in brightness in an attempt to bring the operators' attention to gross errors ($> \pm 50\%$). In fact, there was a very slight but insignificant decrease in performance under conditions of enhancement. As pointed out in the report on Phase I of this research program (Vallerie, 1967), for enhancement to be effective, the primary encoding technique (changes in the rate of motion) must be less than adequate for conveying the information required by the operator to control the vehicle. Based on the performance scores, it would appear that motion was able to convey all the information the operators could effectively utilize and that enhancement merely provided redundant information which did not improve the operators' ability to discriminate input signals.

It should also be pointed out that, because of the nature of the simulator used and the preset error tolerances, gross errors ($> \pm 50\%$) did not occur very frequently until the loop had "opened up" and the operator was beginning to "level off" due to the difficulty he was having in maintaining control within the preset error tolerances. Only at this level did errors frequently exceed 50% and enhancement come into full play. Evidently, the operators were fully aware of these errors using motion cues alone and they could do little to correct them when emphasized through enhancement. This lends further support to the hypothesis that motion is a very effective stimulus dimension for encoding displays for peripheral viewing.

The final analysis of the results concerns those differences associated with the operators who participated in the study. The experimental design employed did not permit a legitimate test of the differences between the performance of operators. Since these differences always exist in this type of research, it was not considered important to include this factor as a major variable except as a means for improving the efficiency of the study. However, as seen in Table III, which summarizes the results of the variance analysis, the variance estimate (MS) for subjects indicates a large difference between operators. The variance estimates for the two-way interactions involving subjects also indicate that the various display conditions affected the operators in different ways which is in accord with expectation. More interesting and little expected are some of the comments made by the operators during the study. Most operators, for example, found it difficult to learn the correct display-control relationship in the pitch dimension with the PCI, even though it was set up exactly the same way as the PVD; i.e., inside out. In contrast, the PVD was said to be quite natural and the control vectors in both control dimensions were quickly learned and easy to follow with the control stick. At first, most operators stated a preference for the PVD, but after approximately an hour's practice, the PCI was considered more desirable by all of them. Operators were always given knowledge of their results and it is possible that their better performance with the PCI after practice could have influenced their statements.

During practice, a few of the operators purposely tried looking directly at the PCI with their central vision. They found that they experienced many control-display reversals and could not control pitch as well as when the display was kept entirely in the periphery. This was not true of the PVD.

Other comments, made by the operators, were concerned with the interference of flicker with the perception of motion under the enriched conditions involving the control of airspeed. The fast flicker (4hz) which indicated excessively high airspeed was reported to cause interference. It is possible that this phenomenon could explain the degradation in pitch and roll performance when airspeed signals were incorporated in the displays. Since airspeed signals were presented only on the central PVD, and not on the two side PVD's, only roll performance should have been affected by such interference. However, as explained above, both pitch and roll performance were affected to a significant degree; a slightly greater effect for roll than for pitch; viz., a reduction of six points versus four points. This difference, though small and insignificant, does yield some credance to the operators' statements involving perceptual interference. Since the PCI was a single display, such interference would be expected to reduce performance equally. But again, there was a slightly greater effect on roll than on pitch; the differences between the two channels being of the same magnitude as with the PVD. In view of these considerations, it seems reasonable to state that the reported interferences did not affect control performance in a logical or detectable fashion.

SUMMARY AND CONCLUSIONS

During Phase I of this research program, a laboratory study was conducted to determine the effectiveness of peripheral vision displays for presenting dynamic information for use in difficult control tasks. It was found that control performance deteriorates as visual switching between conventional displays, designed for central vision, increases and that peripheral displays can be successfully utilized to overcome these adverse effects. Visual switching was defined as including eye movement, accommodation, and convergence.

Having demonstrated the utility of peripheral displays, the objective of this second phase of the program was to develop and evaluate a number of display concepts which appeared promising in view of the known capacities of peripheral vision, the state-of-the-art in display techniques, and the constraints of the operational environment. Concepts not readily implemented in aerospacecraft cockpits were not given consideration, rather concepts already developed and deemed operationally feasible were selected for further investigation. Among these were the Para-Visual Director (PVD) and the Peripheral Command Indicator (PCI) which are the only two peripheral display systems presently in operational use and commercially available. Other concepts for display involved the use of flicker to encode airspeed signals and differential brightness to improve the discriminability of input signals. These concepts were subjected to evaluation during a laboratory study under controlled experimental conditions. The relative merits of the various concepts were investigated using an adaptive loop simulator which presented dynamic teaching information and measured operator performance in three control dimensions; viz., pitch, roll and airspeed.

Results of this study clearly indicate that the operators achieved a significantly higher level of performance with the PCI than with the PVD. The PCI, evidently, demands less work of the operator since the integration of the pitch and roll dimensions is performed on the display itself rather than requiring the operator to perform this operation as is the case with the PVD. It was also found that performance in pitch was worse than roll regardless of the display being utilized at the time. This suggests that special consideration should be given to the pitch dimension in the design of peripheral displays.

The results of the study also indicated that the addition of airspeed degraded performance in both pitch and roll to a comparable extent. This conclusion provides corroborative evidence that man possesses a limited capacity for processing information in control tasks such as the one employed in this study. The control of airspeed, apparently, added an additional task to an already high workload involving the control of pitch and roll.

Performance could not be improved by enhancing the peripheral displays with differential brightness in an effort to bring the operators' attention to gross errors in pitch and roll. It appeared, therefore, that motion, the primary encoding stimulus, was able to convey all the information the operators could effectively utilize in this task and that enhancement merely provided redundant information which did not improve their ability to discriminate input signals. This lends further support to the hypothesis that motion is a very effective stimulus dimension for encoding peripheral vision displays.

The operators who participated in the study reported that the PVD was "natural," quickly learned, and easy to follow with the control stick. At first, most operators preferred the PVD display system, but after practice, considered the PCI more desirable. Some control-display reversals were experienced with the PCI, especially in the pitch dimension, when it was not kept in the periphery but was viewed with central vision. This suggests that the control-display relationship for any peripheral display should be chosen with care if such reversals are to be minimized in the operational environment. Such reversals could be a serious safety hazard under many circumstances.

In conclusion, it should be pointed out that the adaptive loop method has proved to be a very sensitive and appropriate technique for evaluating displays. Operators were found to learn very quickly as compared with conventional methods involving the use of present difficulty levels. Time consumed in collecting sufficient data to evaluate the displays and time involved in running subjects was far less than usual in studies of this type. These results would suggest the adaptive loop techniques to be a significant tool for the evaluation of displays and controls of all types.

APPENDIX

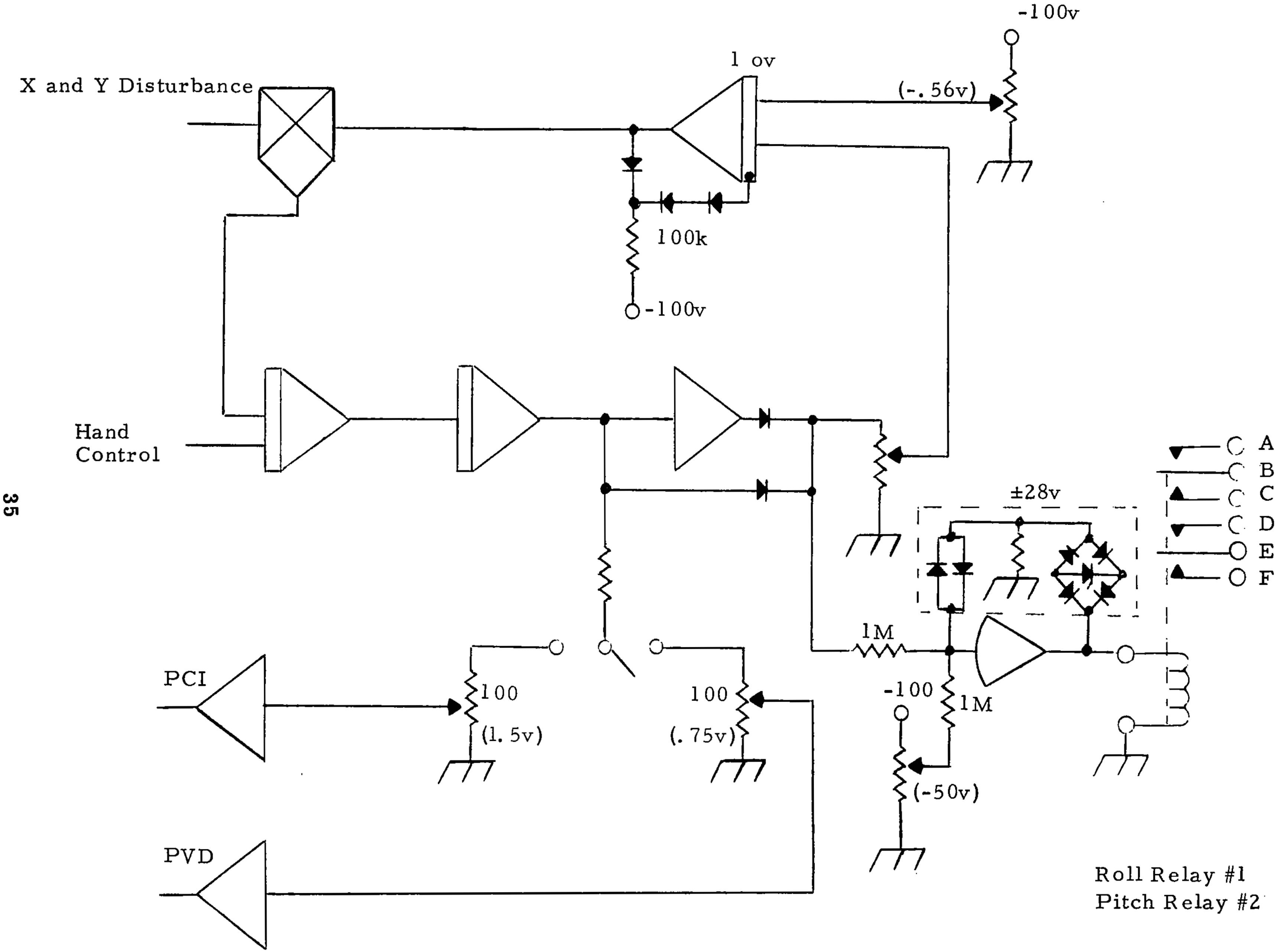


Figure A-1. Pitch and Roll Circuit

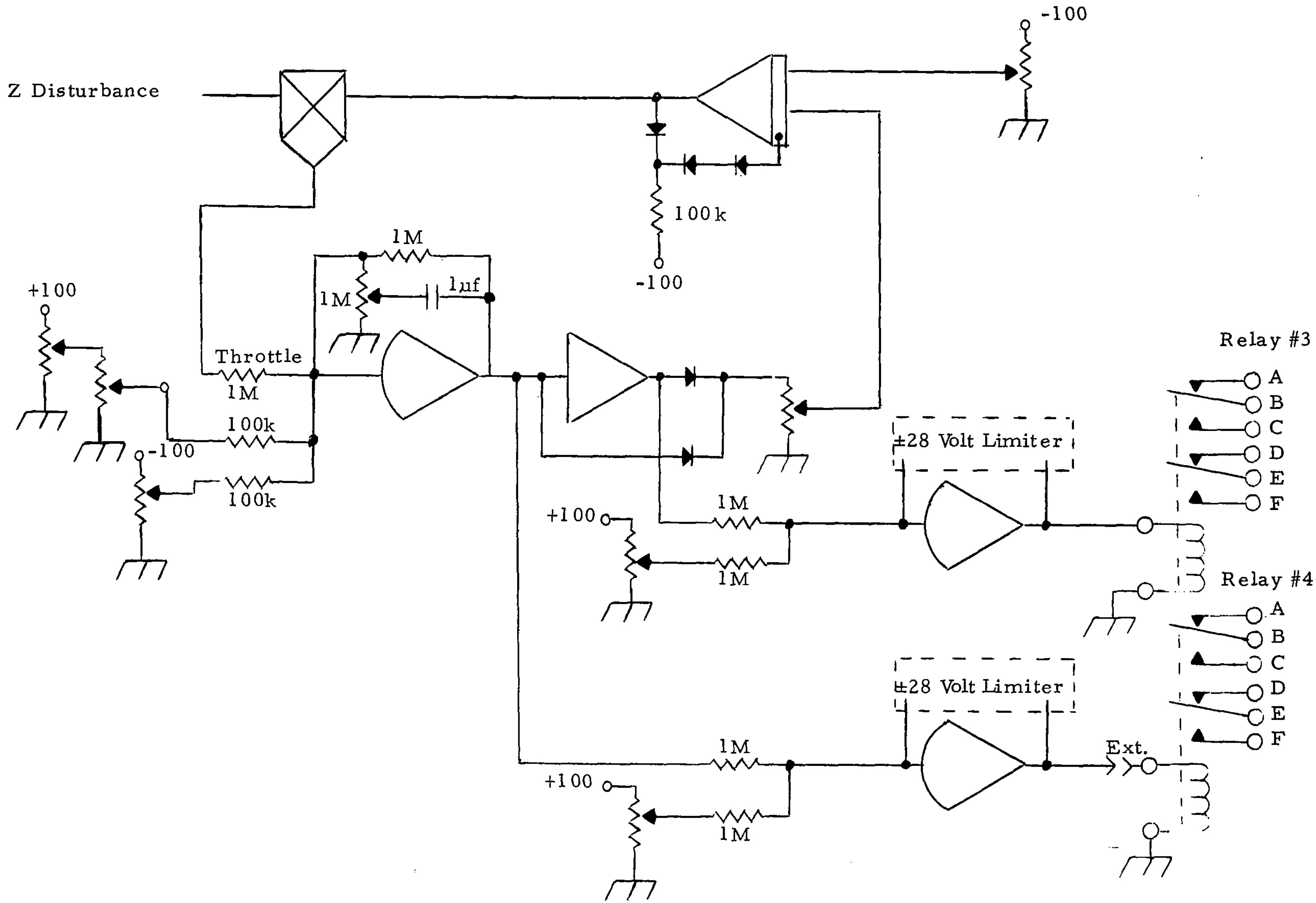


Figure A-2. Airspeed Circuit

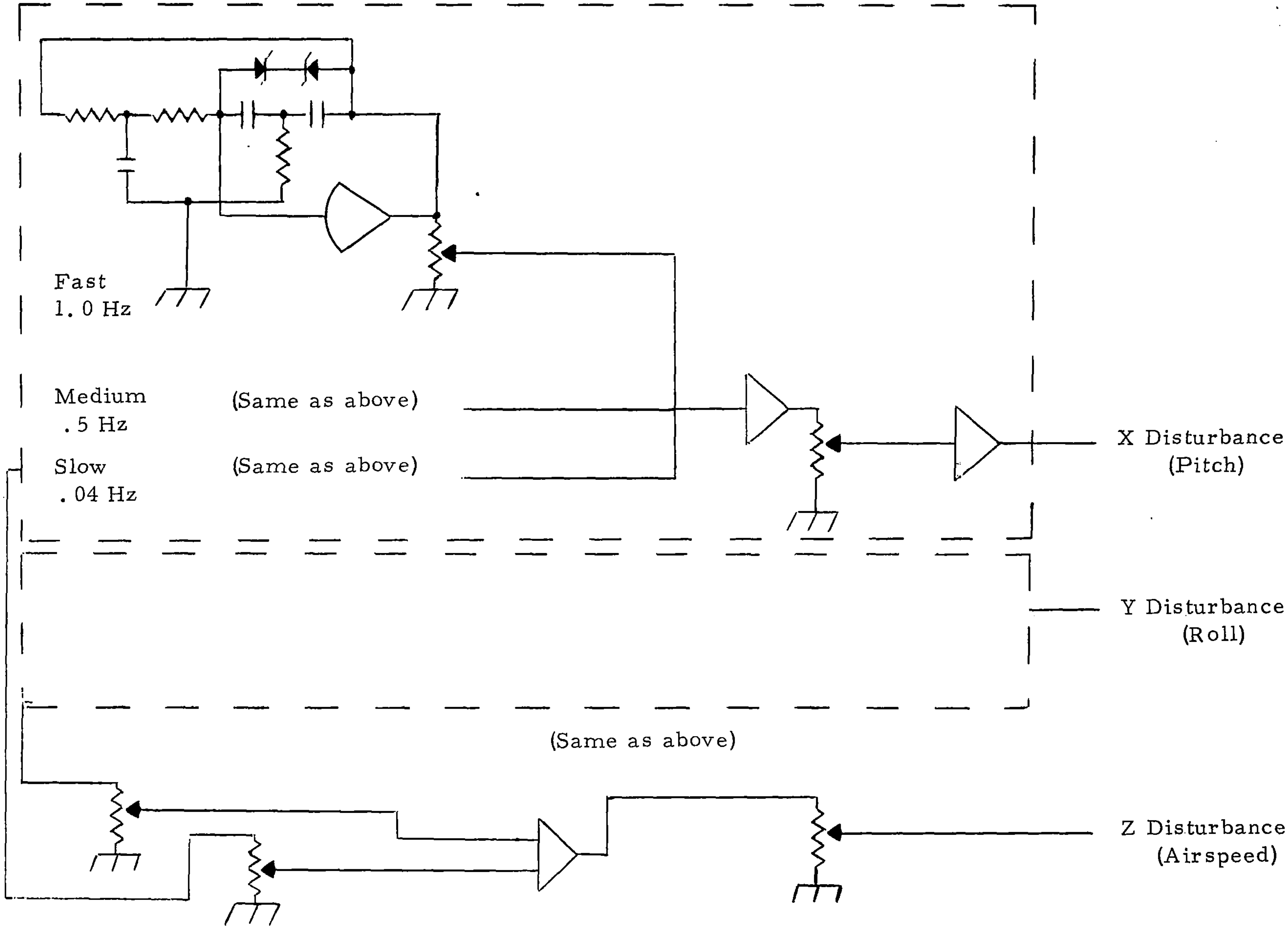


Figure A-3. Disturbance Function Generator Circuit

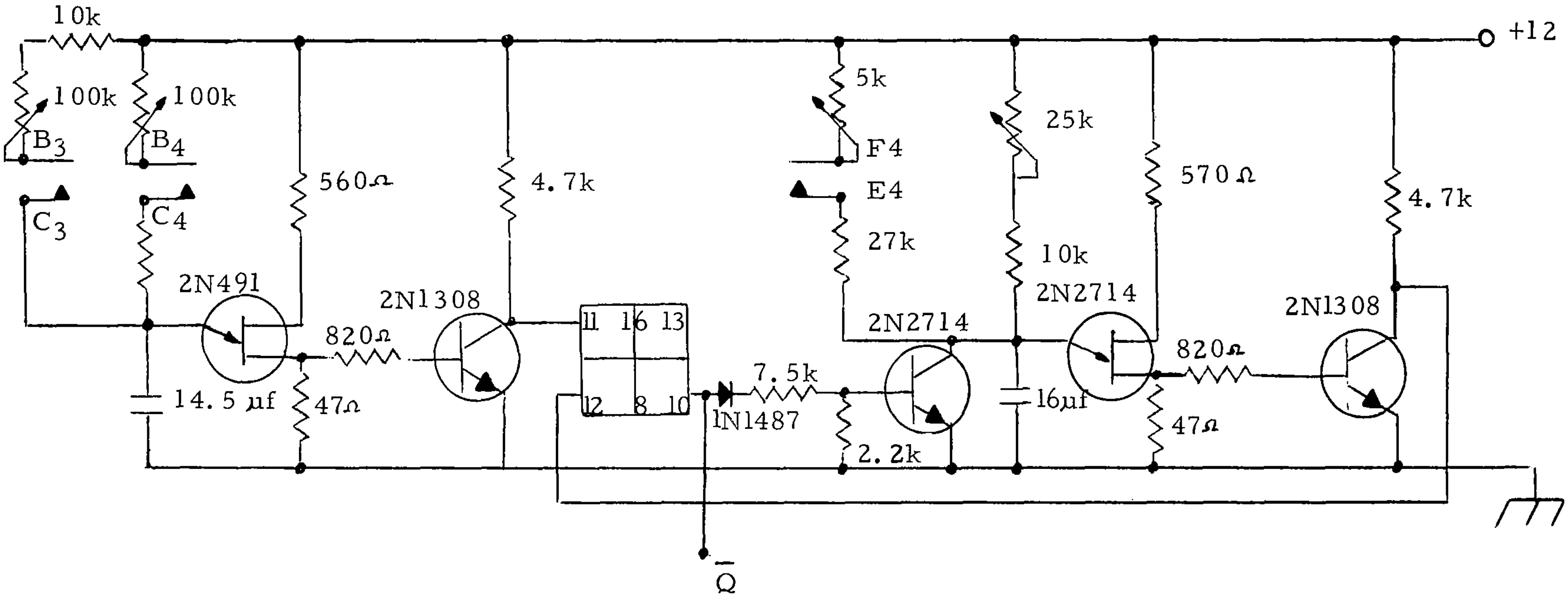


Figure A-4. Intensity Modulator Circuit
(1 of 1)

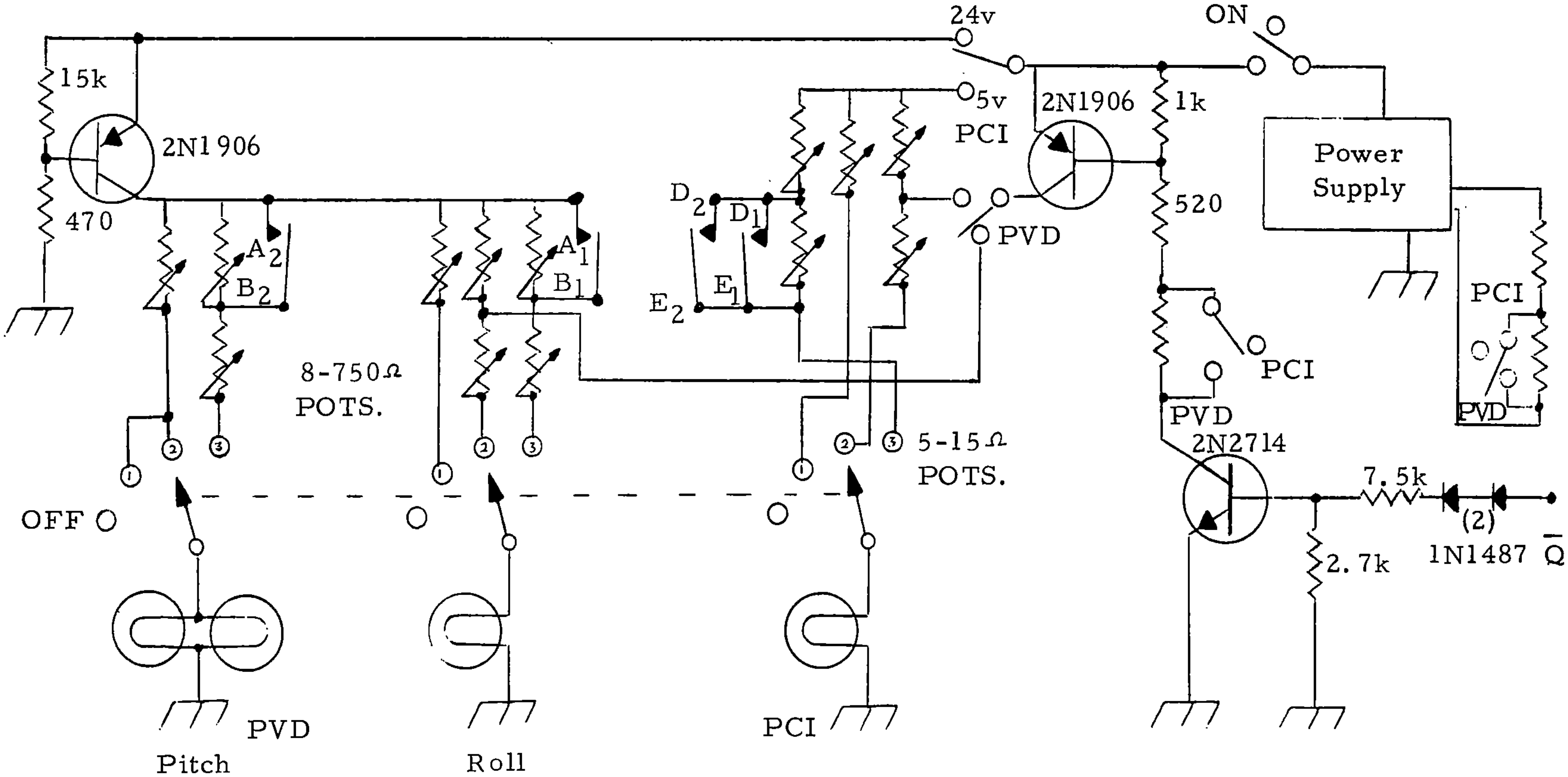


Figure A-5. Intensity Modulator Circuit

(2 of 2)

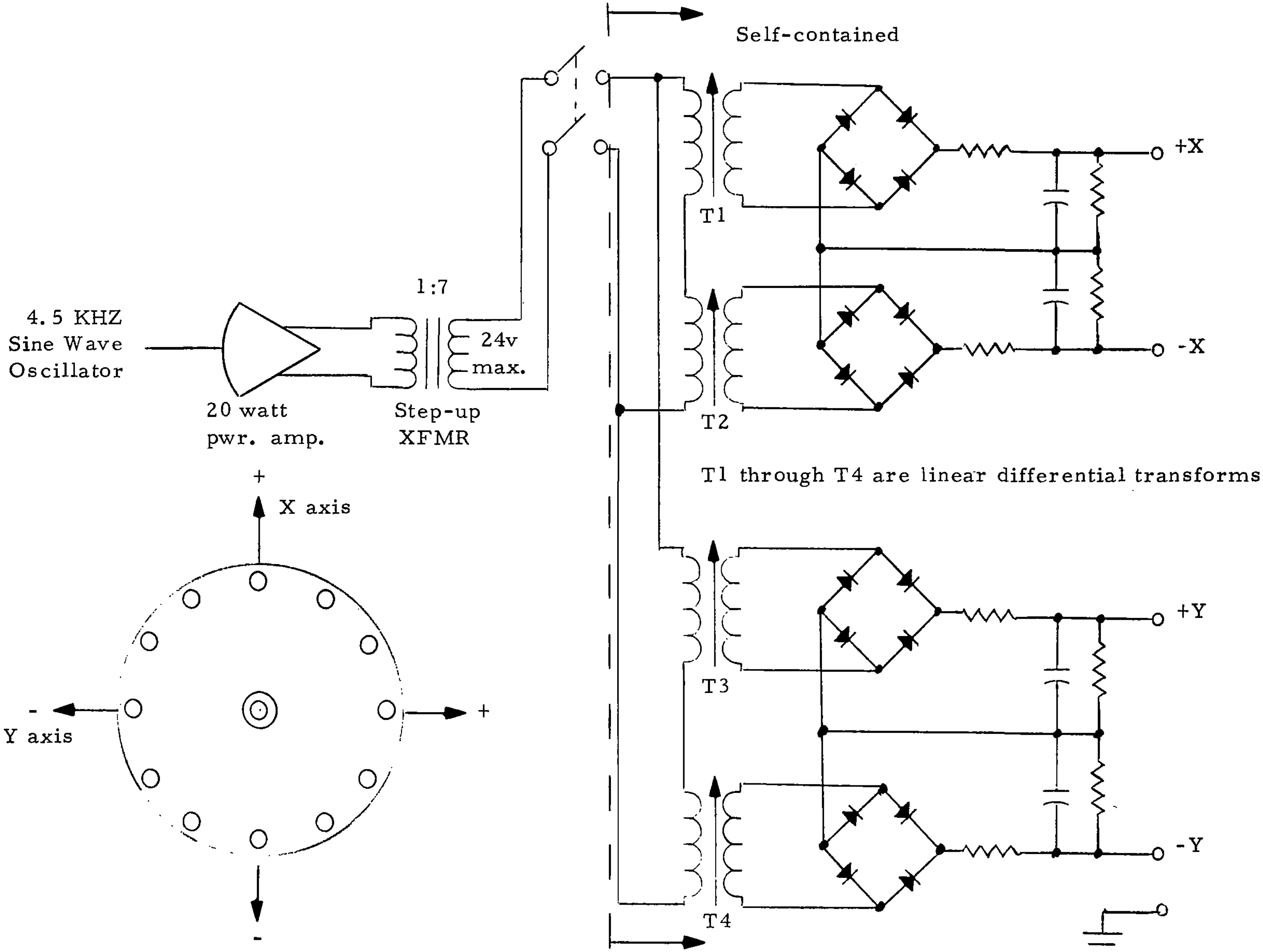


Figure A-6. Pressure Stick Circuit

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