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SPERRY PHOENIX COMPANY *Division of Sperry Rand Corporation* *PHOENIX, ARIZONA*

final report

Avionics Requirements for All Weather Landing of Advanced SST's

Volume II
State-of-the-Art Review of All Weather Landing System Techniques

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Prepared By S. S. Osder

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AWL Displays	D. J. Hampton W. H. Boudreau
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SECTION III

STATE-OF-THE-ART ANALYSIS OF DISPLAY TECHNIQUES FOR AWL

A. HUMAN FACTORS

1. Introduction

The most difficult problem and perhaps the major problem area in all weather landing relates to human factors. Human factors has become a distinct technical discipline with its own formalized methodologies. The human factors technology has made its main contribution to all weather landing by focusing on the significant problems associated with man-machine task allocations within the aircraft cockpit. Research over the years has defined the nature of the sensory and motor processes used by the human pilot in controlling the aircraft. An extensive body of literature has been concerned with the perceptual mechanisms and information processing in relation to the role of the aircraft pilot. While many sensory channels are involved, the most important are obviously visual. The critical problems of all weather landing operations involve two separate but partially related aspects of the human pilot's response to visual cues. They are as follows:

- How should information be presented to the pilot so that he can monitor the progress of an automatic landing or control the aircraft to a proper landing when weather conditions preclude visual contact with the runway?
- How should flight control and status displays be presented so that a transition from instrument (IFR) to visual (VFR) conditions can be made prior to touchdown; and what are the factors (position, velocity, time, aircraft dynamic characteristics, visibility, etc) which should preclude such a transition?

2. Flight Control Displays and Allocation of Crew Duties

The first problem is the classic one of defining the best flight control information display. The critical nature of the all weather landing mission, however, complicates this problem somewhat. Visual cues from various concurrent sources of information are generally used in a time shared manner. To minimize the workload of the eye, the design of flight control displays require that certain principles of arrangement be observed. Displays must be grouped in accordance with categories of functions and their inter-relationships. An optimum design allows the various instruments or symbols to be linked with a minimum of eye movements. Also, displays corresponding to more important parameters must be located so that the necessary attention priorities are readily obtained. In the final segments of a low or zero visibility landing we are confronted with the fact that many of the displayed flight parameters are critical and demand a high degree of visual attention. The flight director - attitude indicator may display the key information at this time but airspeed, radio altitude, barometric altitude, rate of descent, and ILS deviation information are also extremely critical. As the approach progresses, available response time shrinks and the need to maintain an adequate surveillance or sampling of the different flight instrument symbols becomes more important. It is under such conditions of stress and loading of the visual sensory channels that human factors studies have revealed a tendency toward eye fixations on a central or top priority instrument. Such circumstances are conducive to missing a warning display that is located outside of the narrow field of vision existing during the excessive attention span given to the central instrument.

In recognition of the rapid loading of the pilot's perceptual mechanisms during a low visibility landing, a trend has been underway to automate many of the procedures required of the pilot and crew. The introduction of automatic throttle controls is a good example of attempts to reduce pilot workload. Increased automation, however, leads to a paradox when considered from the standpoint of the pilot's visual workload. Each automated process, as now implemented, requires some or all of the following additional procedures:

- Set reference parameters (usually dial in on display)
- Initiate operation
- Visually monitor response of control or instrument
- Visually monitor status display for this new function - (includes warning indications and annunciation of automatically sequenced events)

Displays associated with the automated functions contribute to the clutter of the instrument panel. The cluttering is especially apparent when a display system has grown toward a Category III configuration as opposed to the case where it is designed initially for this mission. The complexity of procedures associated with a low visibility landing and the stresses associated with the situation results in many possibilities for human error. They may be in the incorrect setting of a dial, failure to observe an instrument discrepancy or warning indication, or a delay or error in the initiating of events such as gear and flap deployment.

Errors in these categories can never be eliminated but techniques and tactics can be developed to minimize their occurrence and then to compensate for them if they do occur. Improving the presentation of information is a major human factors challenge. Electronic displays which can minimize clutter by easily removing nonessential information offer considerable promise. The use of the auditory sensory channels for transmitting warning information has not been adequately exploited and can probably be used to good advantage in an all weather landing system. Both of these techniques impose new challenges to avionics reliability. As long as the pilot is in the loop, however, the most important approach to elimination of human error effects involves the allocation of crew assignments. In effect, it must be recognized that human errors can occur. The crew procedures, in conjunction with the displays and automated control and decision making devices, must be used to provide a form of massive redundancy that can easily identify and compensate for errors. This requires precisely defined allocation of crew duties and extensive crew training to handle emergency situations. An important objective of human factors research is to help resolve many of the questions that exist regarding allocation of crew duties and to determine effective methods of crew training.

3. Transition From IFR to VFR Conditions

The second human factors problem relates to the pilot's ability to perform a manually controlled, visual landing after penetrating through a zero visibility medium and then sighting the runway in the final seconds prior to touchdown. If he were monitoring cockpit instruments and scanning outside the cockpit for external cues, there are a number of difficulties that make this a very hazardous procedure especially when the aircraft altitude has penetrated below the Category II decision altitude (100 feet). First, there is the problem of time delays associated with alternating the visual perception channels between two sources of information. Reference 27 has defined a 2.39-second lag associated with shifting sight from outside the cockpit to the instrument panel and back outside in accordance with the following breakdown:

Operation	Time (seconds)
Transition to Panel	
Muscle Movement	0.175
Eye Movement	0.05
Foveal Perception	0.07
Accommodation	0.50
Recognition of Instrument Reading	0.80

Operation	Time (seconds)
Transition Back to External View	
Reaction Time	0.175
Eye Movement	0.05
Relaxation of Accommodation	0.50
Foveal Perception	0.07
TOTAL	2.39

When it is considered that only to 5 to 8 seconds remains from 100 feet to initiation of the flareout maneuver, this type of lag would seriously compromise the pilot's ability to perform a manual takeover. Again, cockpit operating procedures could preclude this type of problem by assigning one of the pilots the role of external or real world monitor. However, considerable interest exists in the possibility of alleviating or minimizing this problem with heads-up display techniques. In the category of heads-up display one can include a variety of concepts ranging from projections on the windscreen of elaborate electronic displays to simple peripheral vision cues such as the so-called para visual directors. Descriptions of various heads-up and heads-down instruments will be given subsequently. Despite a strong interest in the heads-up devices, their acceptance in terms of operational use has not been commensurate with the prevalent enthusiasm for their advantages. The slow progress has been attributed to some technical difficulties as well as problems associated with adapting the limited cockpit space to the optical projection equipment. However, the human factors problems for heads-up displays are significant and considerable research remains to be done. Symbology, relative alignment between real world and display, area of the windscreen that can be covered, shall the display be projected to appear on the windscreen or in the real world, and the role of color and light intensity are some of the important factors to be considered.

The question of allowable altitudes for manual takeover depends upon evaluation of pilot capability and possibility of human error resulting from aberrations of the visual perception mechanism. A variety of illusory effects resulting from aircraft accelerations can disorient a pilot and cause the old conflict between trusting the senses or the instruments. The experienced pilot is aware of these problems and is generally committed to accepting the judgment of the instrument rather than his senses. How does he respond during conditions of fatigue and under the stress of a low visibility landing when such illusions might occur as visual contact with the runway is first made?

The seriousness of this problem has not been thoroughly evaluated. The problem is stated as a serious one despite the fact that its occurrence may be extremely rare. Because of the stringent safety requirements, even one occurrence of mild disorientation in 100,000 landings may be excessive; for if only a small fraction of such disorientation leads to a landing accident, the desired safety objective cannot be met. The stimulation of the human vestibular apparatus by various aircraft accelerations and the resultant reflexive movements of the eyeballs plus the conflict of sensory information supplied by the eye and the vestibular organs lead to several well-known errors in perception. The so-called oculogyral illusions (apparent movement of fixed objects following rotary motions) and oculogravic illusion (apparent displacement of objects as a function of normal acceleration) and other motion induced illusions are known to be more pronounced during rapid and large scale maneuvers (conditions not encountered during a normal landing approach); nevertheless, even secondary levels of these perceptive aberrations could be significant factors in pilot takeover of a low visibility landing. The unreliability of the pilot's judgment based on body sensory mechanisms has taught him to trust his instruments; but what will constitute the pilot's reference system when he takes over the aircraft in order to execute a manual landing based on his visual contact with the runway?

One type of problem illustrating this point is a situation that has been encountered in some automatic approach flights when a heads-up pilot assumes control of the aircraft after he sights the runway lights. When the automatic system has aligned the aircraft with the center of the runway but with the necessary crab angle to cope with a strong crosswind, pilots have responded to the initial view of the runway with incorrect lateral maneuvers. Looking for visual cues by sighting straight through the windscreen and then suddenly observing the runway approach lights through the side of the windscreen can lead to the illusion that the aircraft is misaligned with the runway. It has been suggested that some types of windscreen displays can avoid this type of illusion by providing a greater awareness of the crabbed approach. Other situations that could lead to perceptive errors may occur during windshear conditions. If the automatic system is successfully accommodating to windshear, it is producing a continuous pitch rate and yaw rate (bank angle). Under these circumstances, small values of the motion induced visual illusions may impede the ability of the pilot to assume manual control with only a few seconds remaining before touchdown. Additional research is needed to establish criteria for pilot takeover of automatic approaches. The critical problem exists in the Category III procedures. A key question that remains to be answered is what is the minimum altitude at which manual takeover should be permitted in a non-emergency situation.

B. DISPLAY CONCEPTS

1. Introduction

Display concepts for aircraft involve the integration of many individual instruments and many sources of information. They involve consideration of the entire cockpit so that concern with only one aspect of an aircraft's mission such as the landing functions can not be expected to dictate the characteristics of the flight instrument displays. However, it would make sense to have the low visibility landing functions provide a dominant role in defining the nature of the displays since this aspect of flight makes the most critical demands on display instruments.

Flight control displays may be discussed from many viewpoints. Human factors considerations are often concerned with such details as lighting, readability, and form. For example, evaluations of circular scale or linear scales, moving pointers or moving scales, and single pointer or multiple pointer concepts are often the concern of human factors studies. In aircraft displays, a continuous dialog between human factors research engineers and pilots has been in progress for 2 decades regarding suitability of inside-out or outside-in presentations. The inside-out view is, in general, the more accepted approach for aircraft. The aircraft is seen as a fixed reference and the world moves with respect to the fixed reference. Thus, in a horizon indicator, the inside-out view shows the aircraft wing symbol horizontal with respect to a frame of reference within the aircraft but the horizon is rotated as the aircraft rolls or pitches. The reverse concept of a moving aircraft has been considered for spacecraft displays. L. J. Fogel has presented a good summary of various viewpoints on this subject in reference 28. It is also noted that Fogel has advocated the kinesthetic analog or so-called kinalog display which is a blending of the outside-in and inside-out symbology. Discussions of these basic concepts, however, are beyond the scope of this report. The intent of this section on displays is to provide a historical perspective on how various AWL display concepts have evolved and to examine some of the trends in this field now underway.

While there are obviously many ways to classify or categorize integrated display concepts, the descriptions which follow consider four main groupings. They are as follows:

- Electromechanical instrumentation using vertical and horizontal situation displays with vertical tape scales in addition to attitude director indicator (standard USAF instruments)

- Electromechanical instrumentation using circular scale indicators throughout (standard airline approach)
- CRT electronic displays - Pictorial presentation
- Heads-up displays

2. The USAF Standard Aircraft Instrument Panel

In the mid-1950's the USAF's Wright Air Development Center Flight Control Laboratory developed an integrated aircraft instrument panel which has subsequently formed the basis of nearly all USAF aircraft displays. The main feature of this panel was its use of a single reference line which could be scanned across a group of related instruments. This extended lubber line permitted interpretation of information in both a qualitative and quantitative sense. Figure 3-1 shows an arrangement of the standard USAF instruments as they were used in an experimental program that evaluated various integrated controls and display concepts for cargo aircraft in 1958 and 1959. Note that all of the tape displays as well as the attitude director and horizontal situation indicator (center instruments) are inside-out displays except for the coarse altitude display on the far right. The latter display is read in the manner of a household thermometer. The single vertical reference line viewed from left to right provides indication of:

Mach airspeed safe speed	Mach Number
	Airspeed
	(Various scales such as angle of attack g's or radio altitude)
Altitude vertical speed	Vertical speed
	Altitude (fine)
	Altitude (coarse)

Also included on the vertical tape scales are the command cursors which can easily be read qualitatively to define polarity and magnitude of error.

An important feature of the vertical tape displays is its adaptability to meet new requirements. For example, a radio altitude scale may be added in the region of the vertical speed scale or it may be incorporated into a flare-out altitude-speed-angle of attack presentation on the right scale of the Mach airspeed unit. The vertical tape instruments allow the addition of critical landing information within an integrated presentation. In order to include the same types of landing functions in an arrangement of circular scale instruments, the attitude director indicator must bear the burden of the additional complexity.

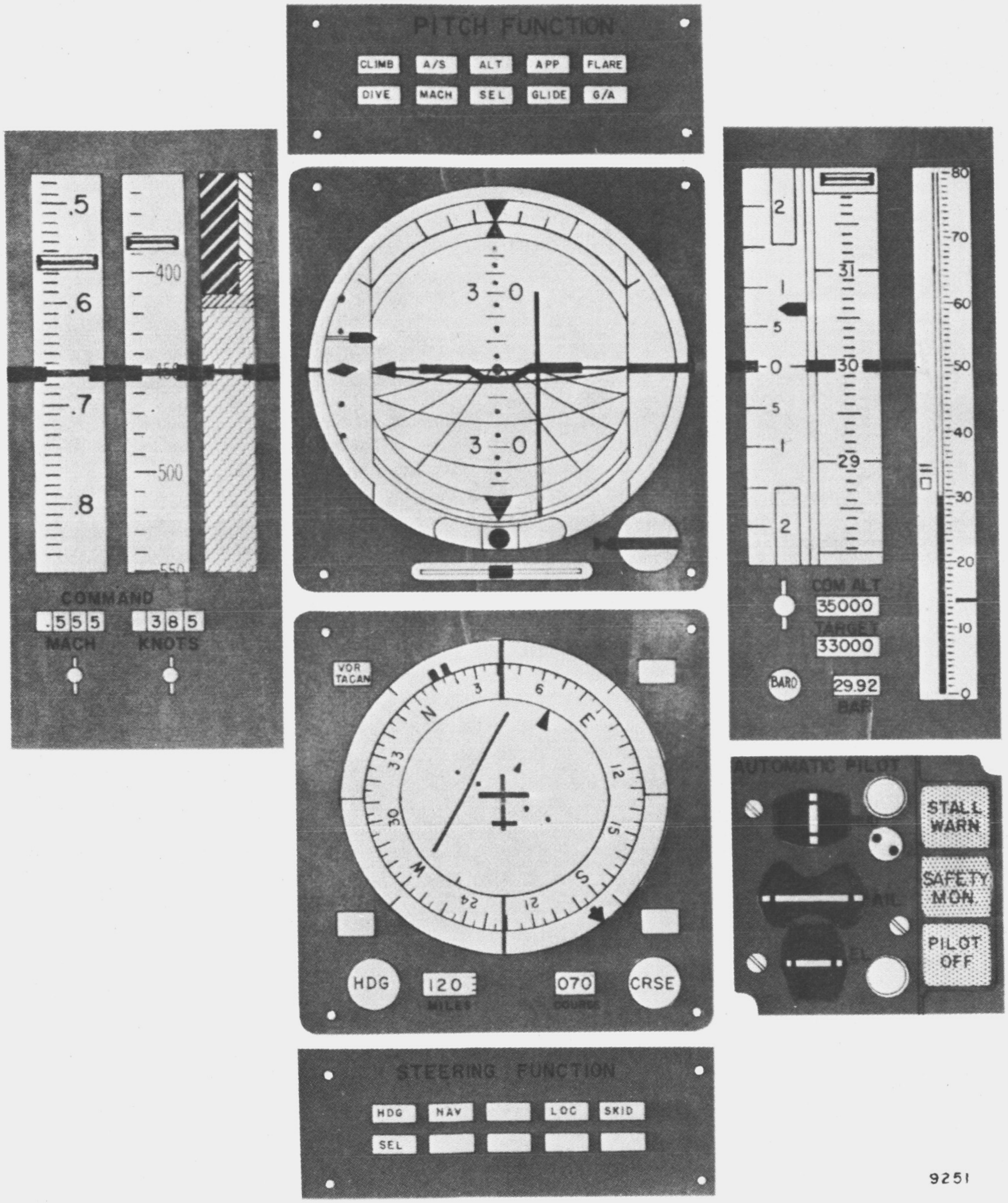


Figure 3-1
Version of USAF Flight Instrument Display

3. Circular Scale Displays - Airline Approach

Commercial airline aircraft displays have followed an evolutionary trend toward more complex attitude director indicators and horizontal situation indicators. As the AWL requirements and procedures have been delineated, the conventional instrumentation was expanded to display the new information. The horizontal situation indicators evolved to interface with various radio navigation systems while the attitude director indicators have grown to encompass lower minima requirements such as expanded localizer deviation scales and radio altitude presentations. Figure 3-2, for example, illustrates the flight instrument displays in the Boeing 727 as equipped for Category II approaches and for evaluation of Category IIIa operational techniques. Shown in this figure are the pilot's instruments and controls and the center panel. The copilot position is not shown in this illustration but it is nearly identical to the pilot's presentation.

3.1 Vertical Situation Displays (VSD)

The trend in vertical situation displays or attitude director indicators can be illustrated by following the evolutionary changes that have occurred in one manufacturer's units. Consider, for example, the Sperry HZ-4 as representative of a basic VSD before the demands for more sophisticated blind landing presentations were incorporated (figure 3-3). Pitch and roll attitudes and pitch and roll commands are displayed on this VSD along with two warning flags, one for the flight director electronics and one for the vertical gyro.

The need for an improved display, incorporating both an expanded localizer and glide slope deviation displays on the VSD, for use during approach and landing, was soon felt. The localizer and glide slope displays were added to the basic HZ-4, as was an inclinometer for obtaining an indication of sideslip angle. Autopilot mode lights, LOC for localizer, and GS for glide slope, were added above the VSD to provide the pilot with still more information concerning the status of his automatic systems. The modified instrument, designated the HZ-4C, is shown on figure 3-4.

Increased requirements for improved readability and a trend toward integrating many displays into one instrument lead to a basic change from a 10.16-centimeter (4-inch) instrument to a 15.24-centimeter (6-inch) instrument. Figure 3-5 illustrates such an instrument, the Sperry HZ-6D. On the HZ-6D, two additional indications were added over and above those which were used on the HZ-4C. They are a speed command display and a "rising runway" which indicates radio altitude over the runway.

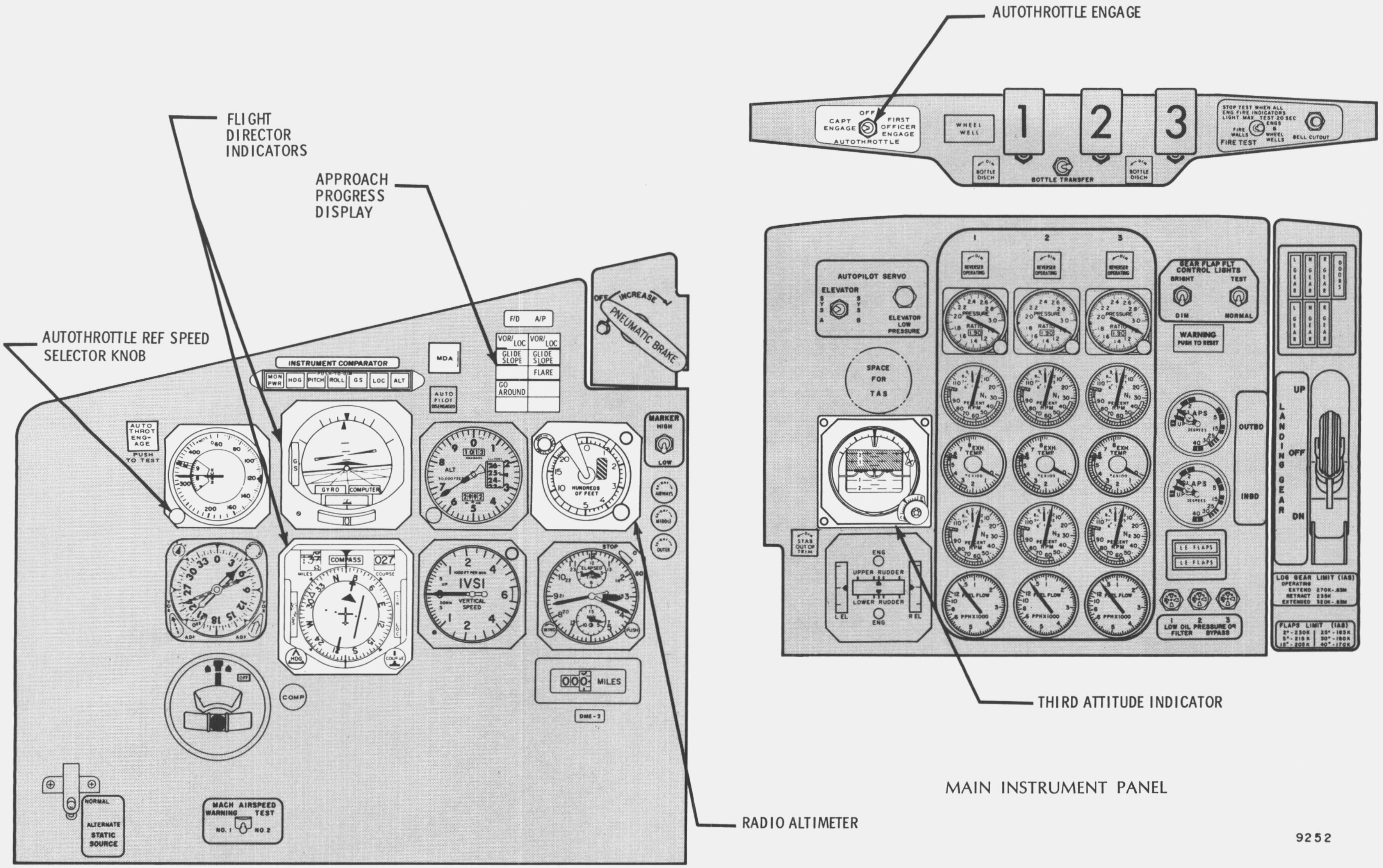


Figure 3-2
Pilot's Instruments and Controls - Boeing 727

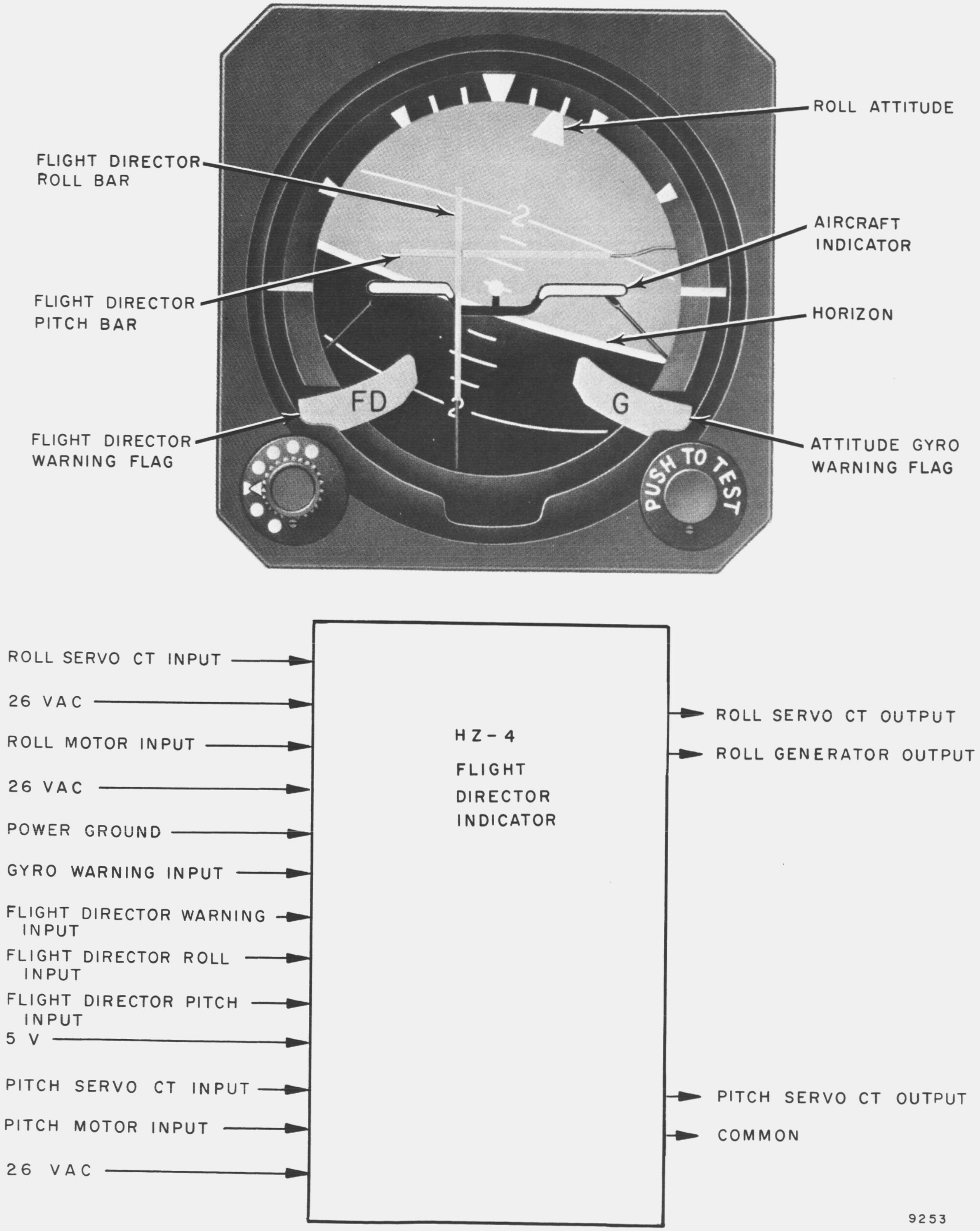
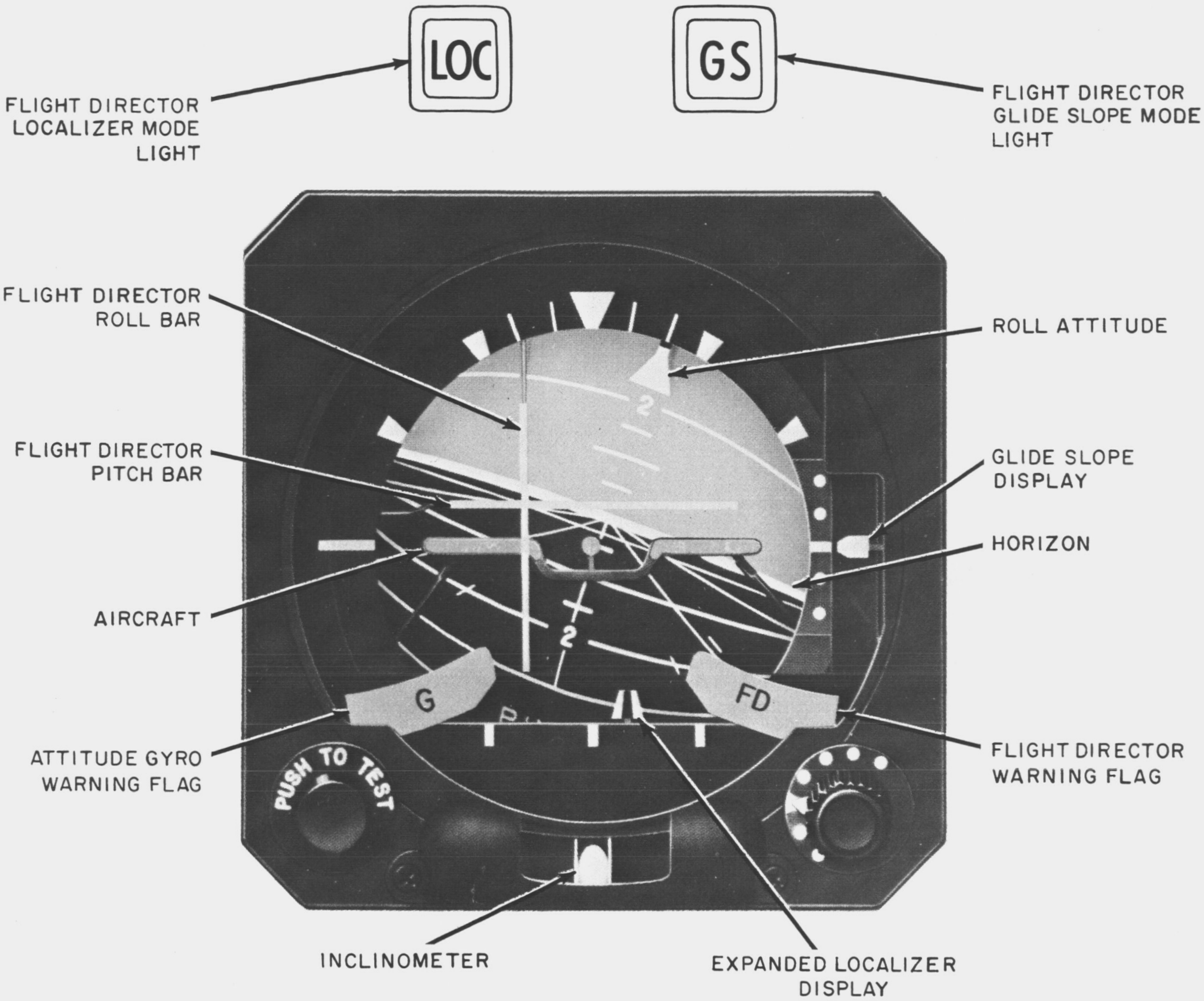


Figure 3-3
HZ-4 Attitude Director



ELECTRONIC INTERFACE BLOCK DIAGRAM

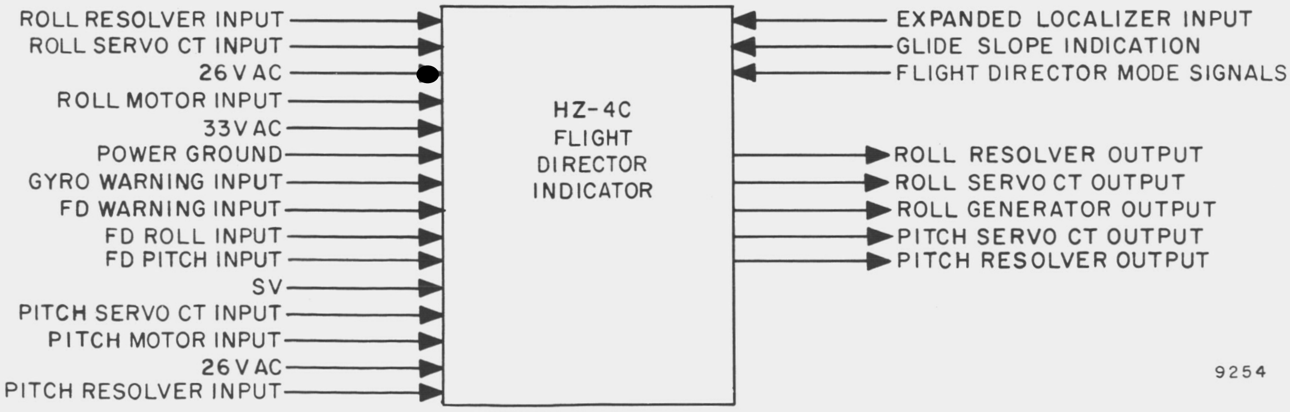


Figure 3-4
HZ-4C Flight Director

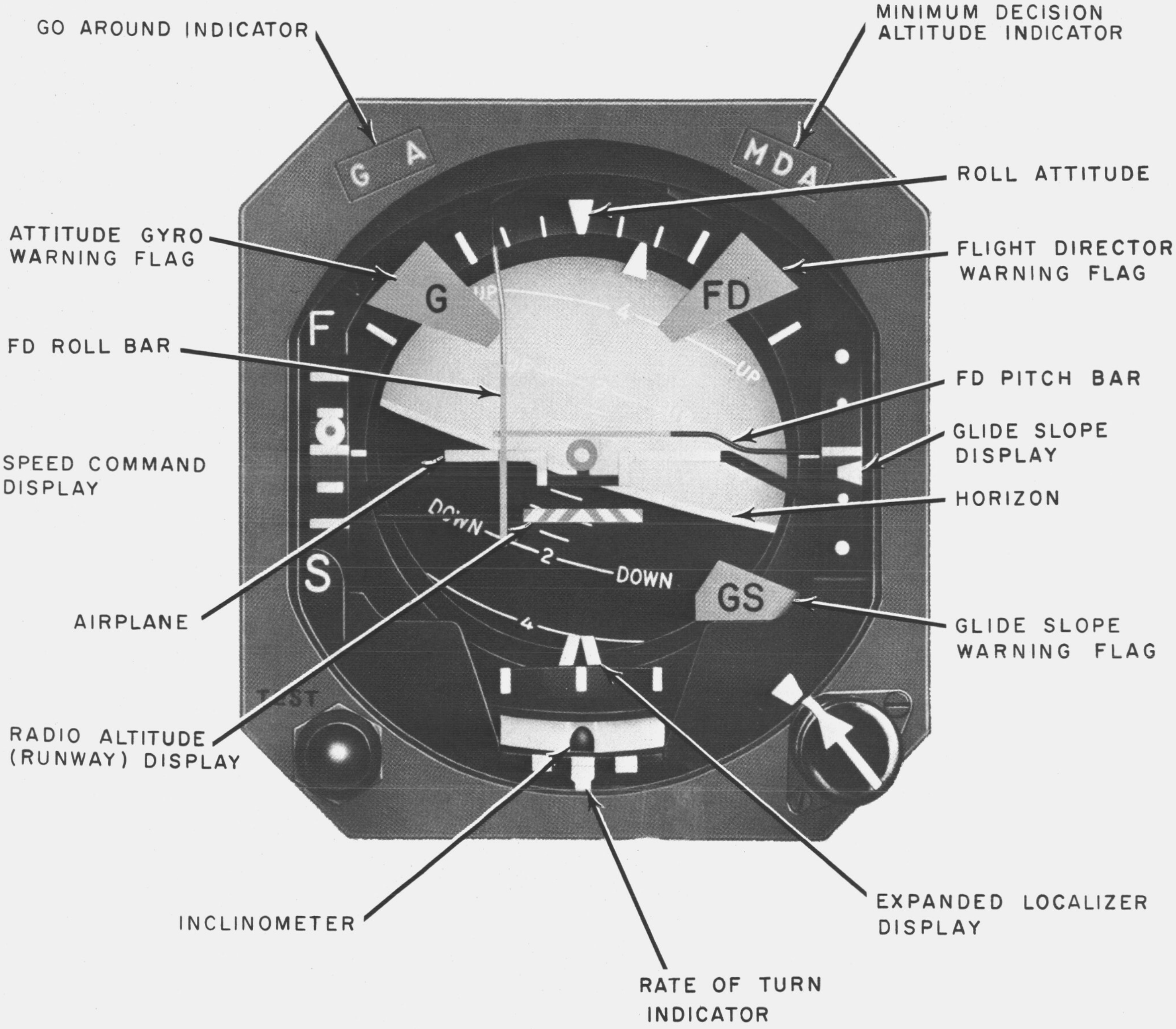


Figure 3-5a
HZ-6D Flight Director

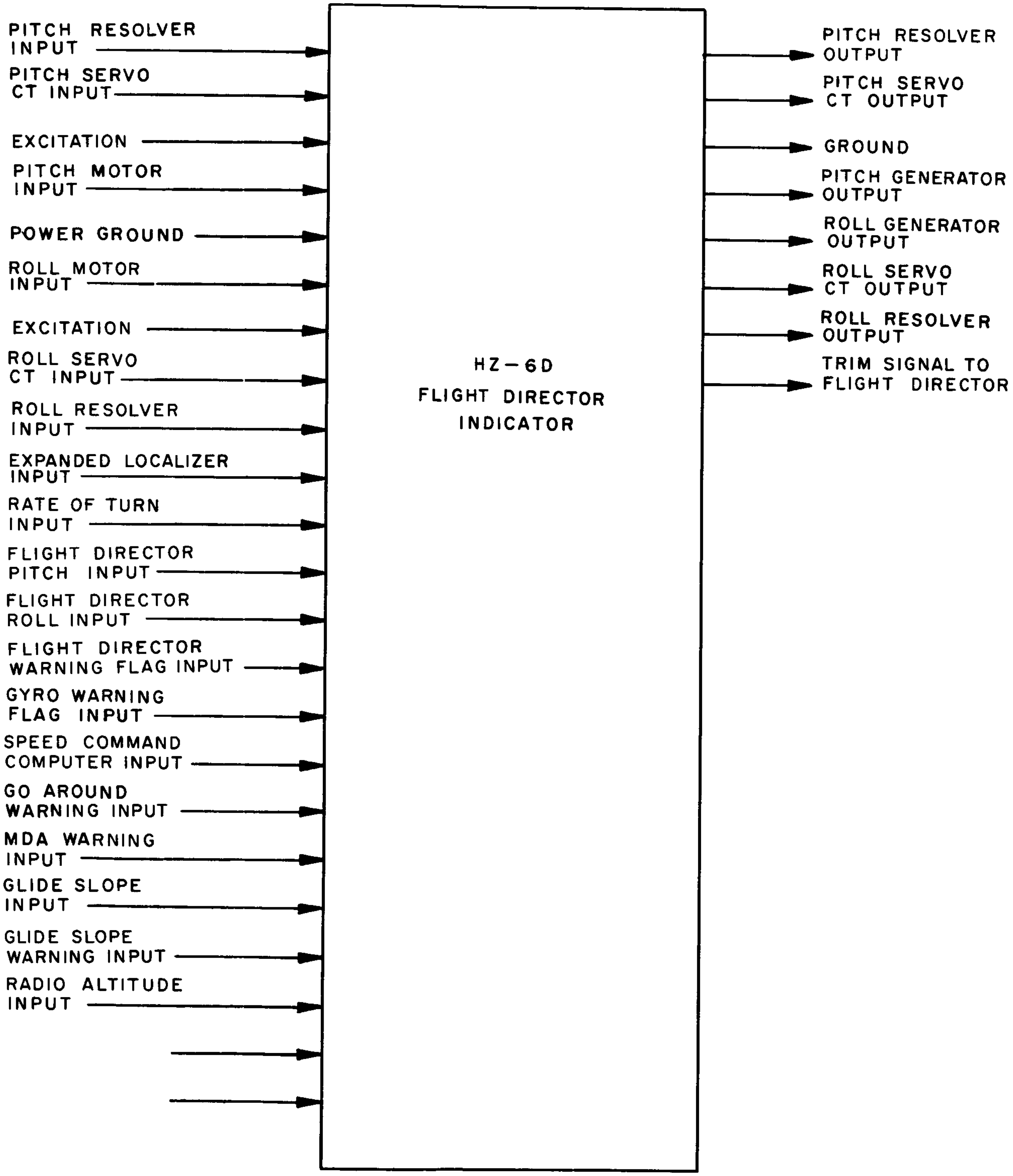


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Figure 3-5b
HZ-6D Flight Director Indicator

Finally, as a further attempt to provide an improved presentation for those final critical seconds just prior to touchdown, an integrated flareout display incorporating both the rising runway and the expanded localizer has been implemented into the VSD. Figure 3-6 illustrates the Sperry AD-200 VSD which features this improved display. Better integrated runway and speed command warning flags were also added to this instrument.

Similar evolutionary changes occurred in other manufacturers' instruments. The Collins 329B series of VSD's are another example of modern VSD's designed for lower minima operations. They are similar to the Sperry AD-200 described above. One version, used with the Collins FD-108 flight director system is shown in the panel layout for the Boeing 727 (figure 3-2). Another version used in a Collins FD-109G system is illustrated in figure 3-7. The main difference between this indicator and Sperry units described previously is the V-shaped command bar which gives an integrated pitch and roll cue in contrast to separate pitch and roll bars.

The Lear Siegler VSD (figure 3-8) includes an attitude ball containing compass heading lines. It is also capable of displaying the usual variety of command and position information.

It is apparent that VSD's are at the saturation point in terms of the complexity of information being displayed by electromechanical means. This observation is confirmed by noting the typical simplified schematic diagram (figure 3-6b). A review of indicators built by one manufacturer over the years illustrates how the increase in the number of parameters displayed leads to increased weight (figure 3-9) and a decrease in predicted reliability (figure 3-10). The conclusion is inescapable that the next advance in displays will not be obtained by a brute force addition to the VSD's described above. It is generally believed that the future advances will be accomplished with all electronic displays.

3.2 Horizontal Situation Indicators (HSI)

This group of displays, often called pictorial deviation indicators (PDI) or radio direction indicators (RDI), provide the horizontal or plan view of the flight situation. The main use of this display for landing operations is the plan view presentation of the aircraft symbol with respect to the desired course. It should be noted that a typical HSI serves as a control set trending away from this to controller as well as a situation display. That is, it is the interface between the pilot and various navigation receivers and computers. By means of this unit, the pilot sets desired bearings and actually transmits

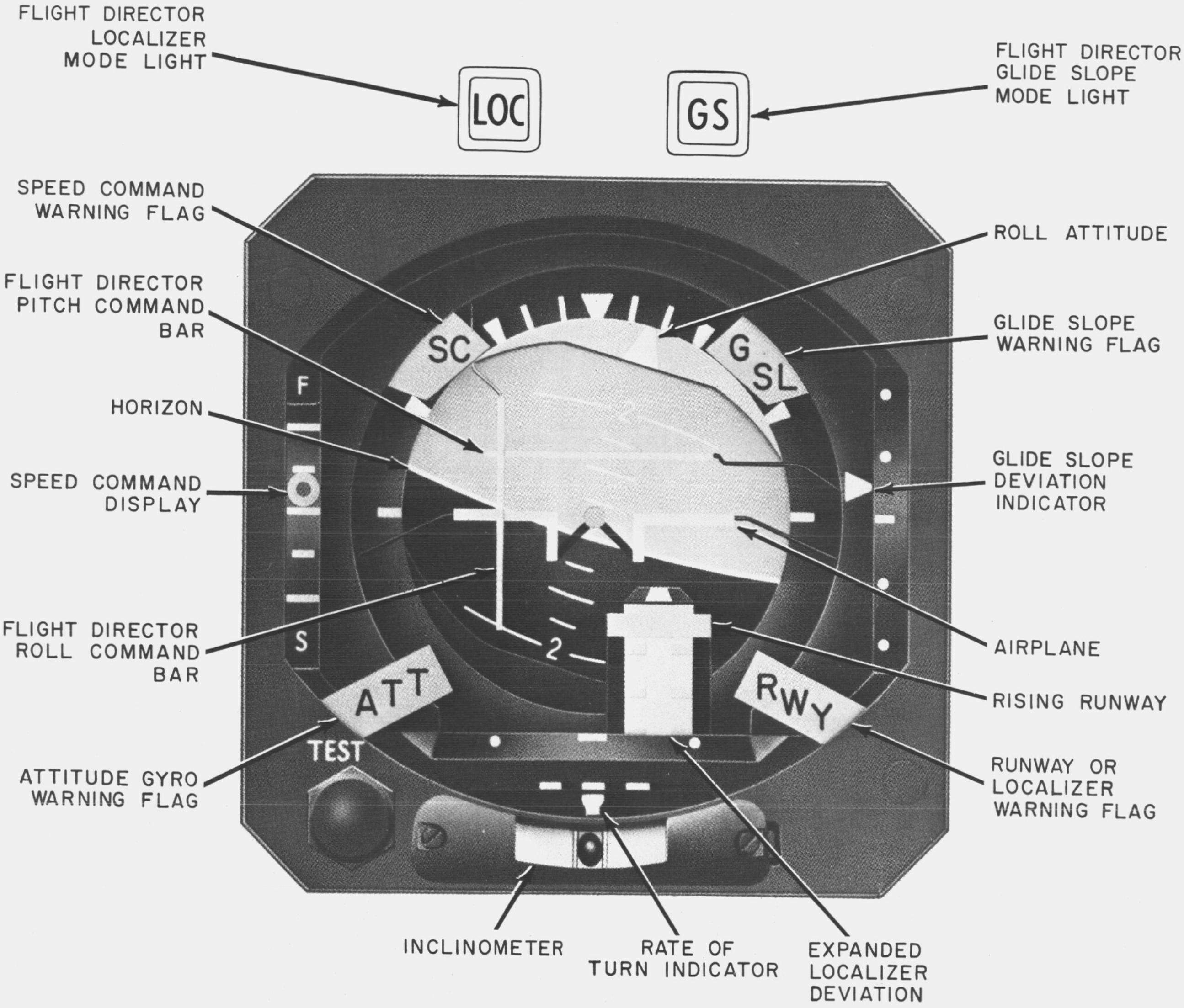

Figure 3-6a
AD-200 Flight Director

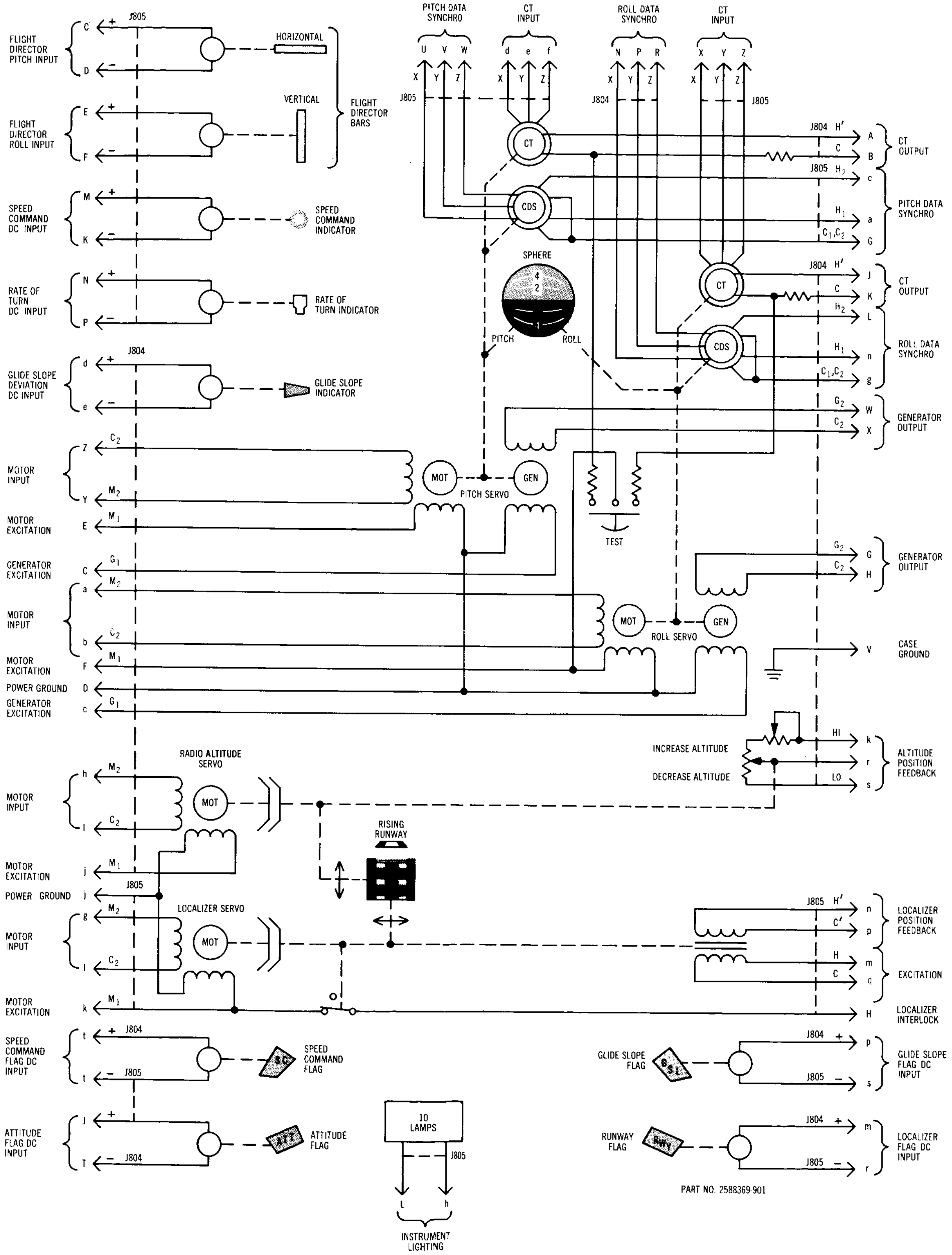

Figure 3-6b
Simplified Schematic Diagram (AD-200)

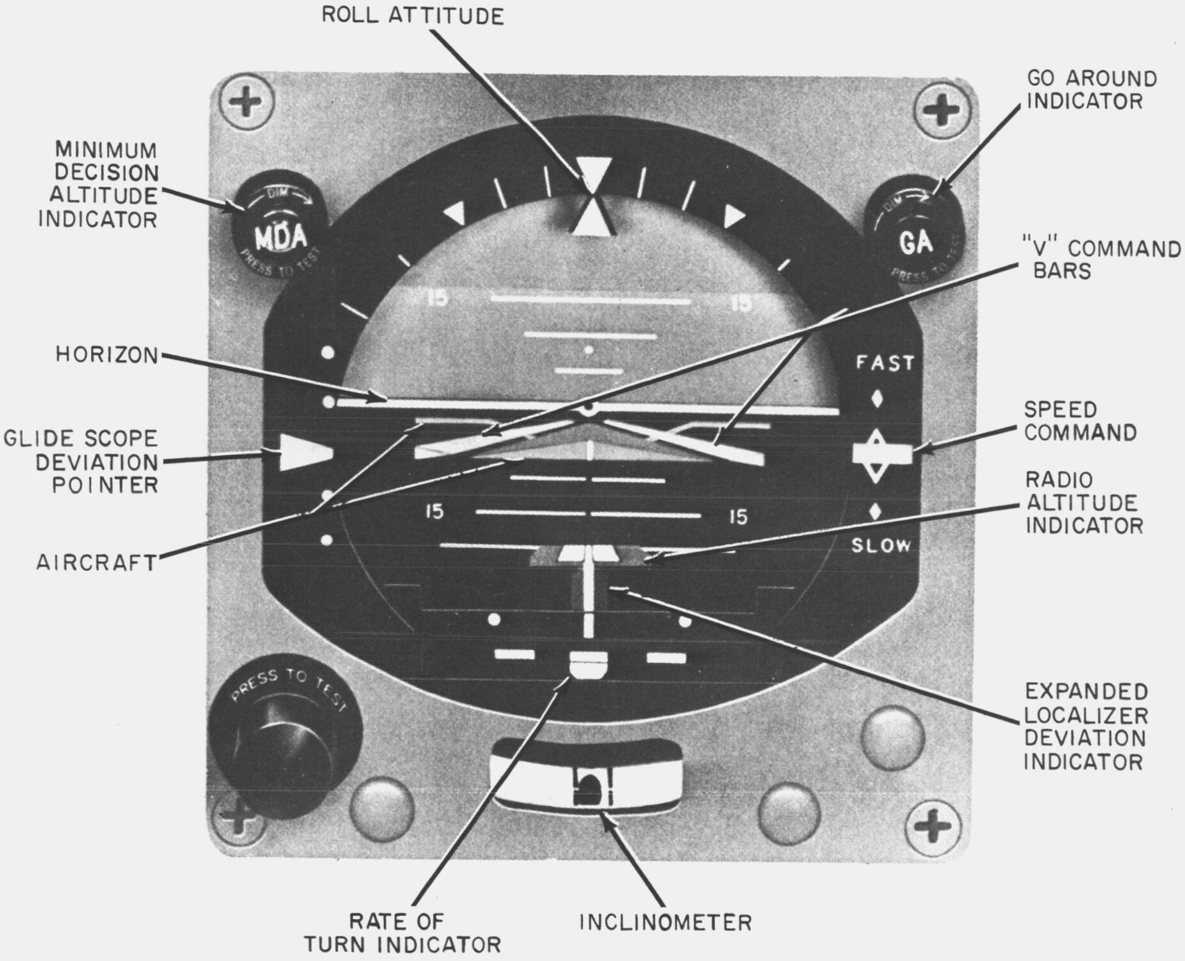

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Figure 3-7
Collins 329B Type Attitude-Director Indicator

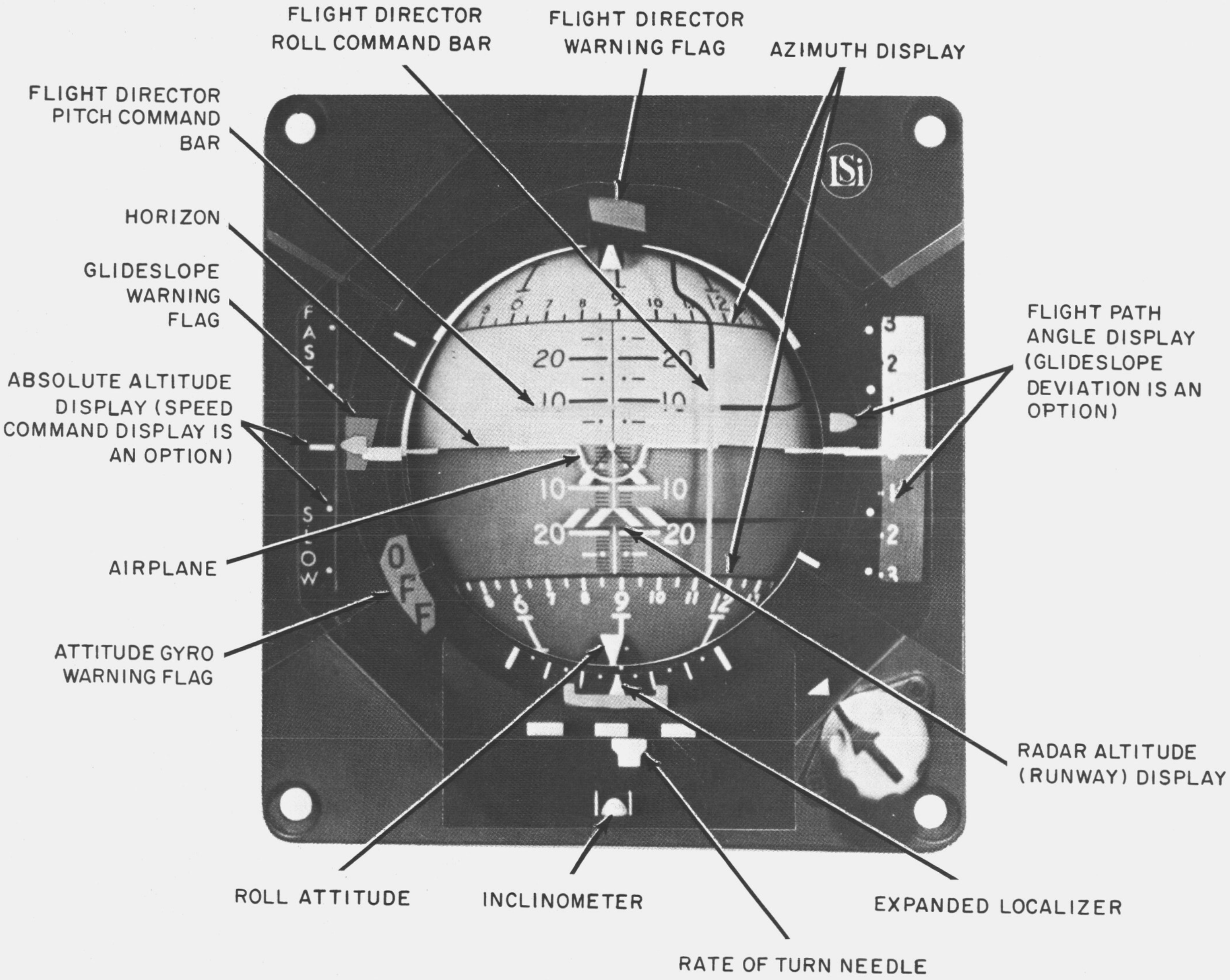

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Figure 3-8
Lear Siegler Three-Axis Attitude-Director Indicator

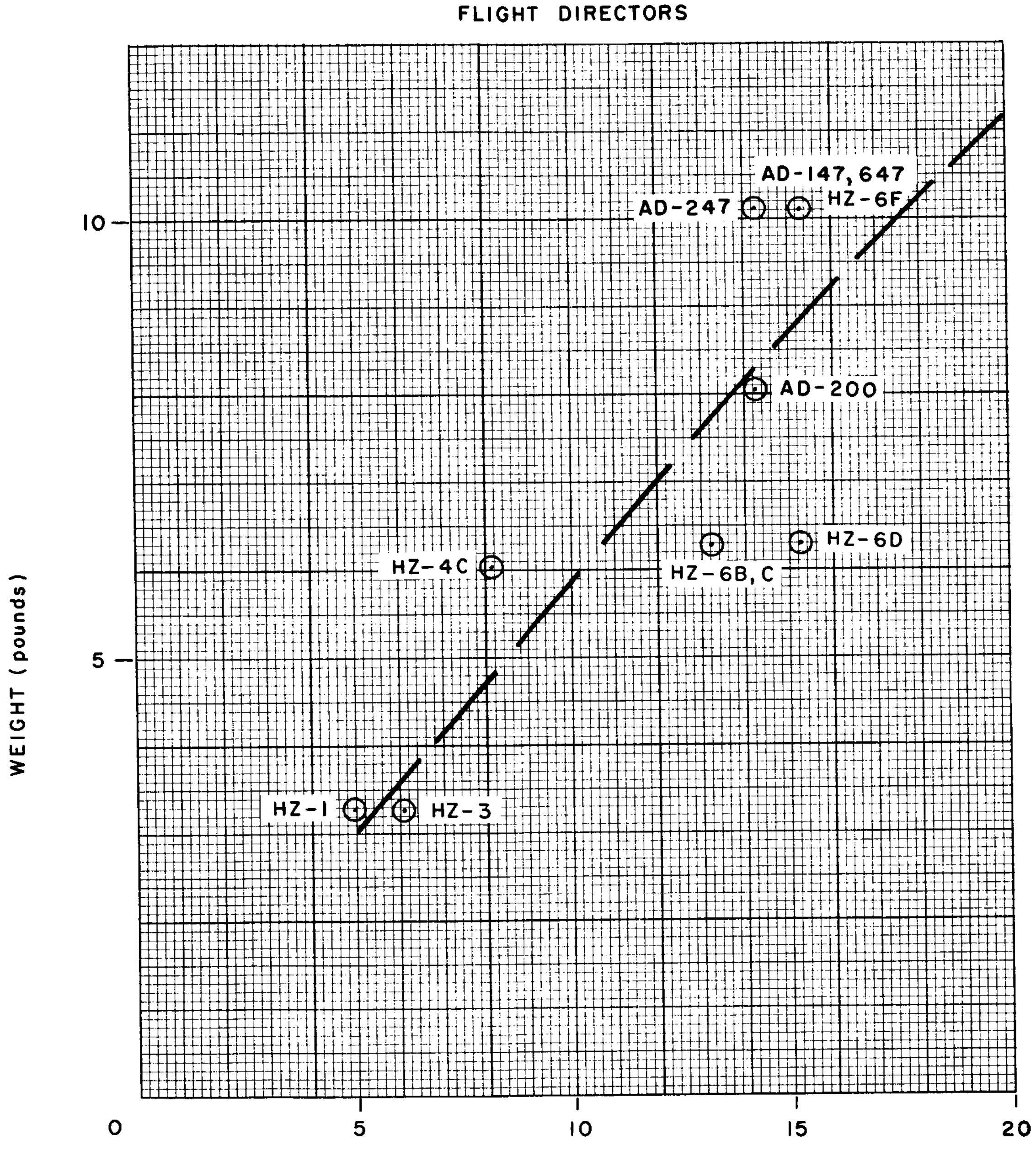

Figure 3-9
Trend of Weight with Increased Sophistication of Attitude-Director Indicator

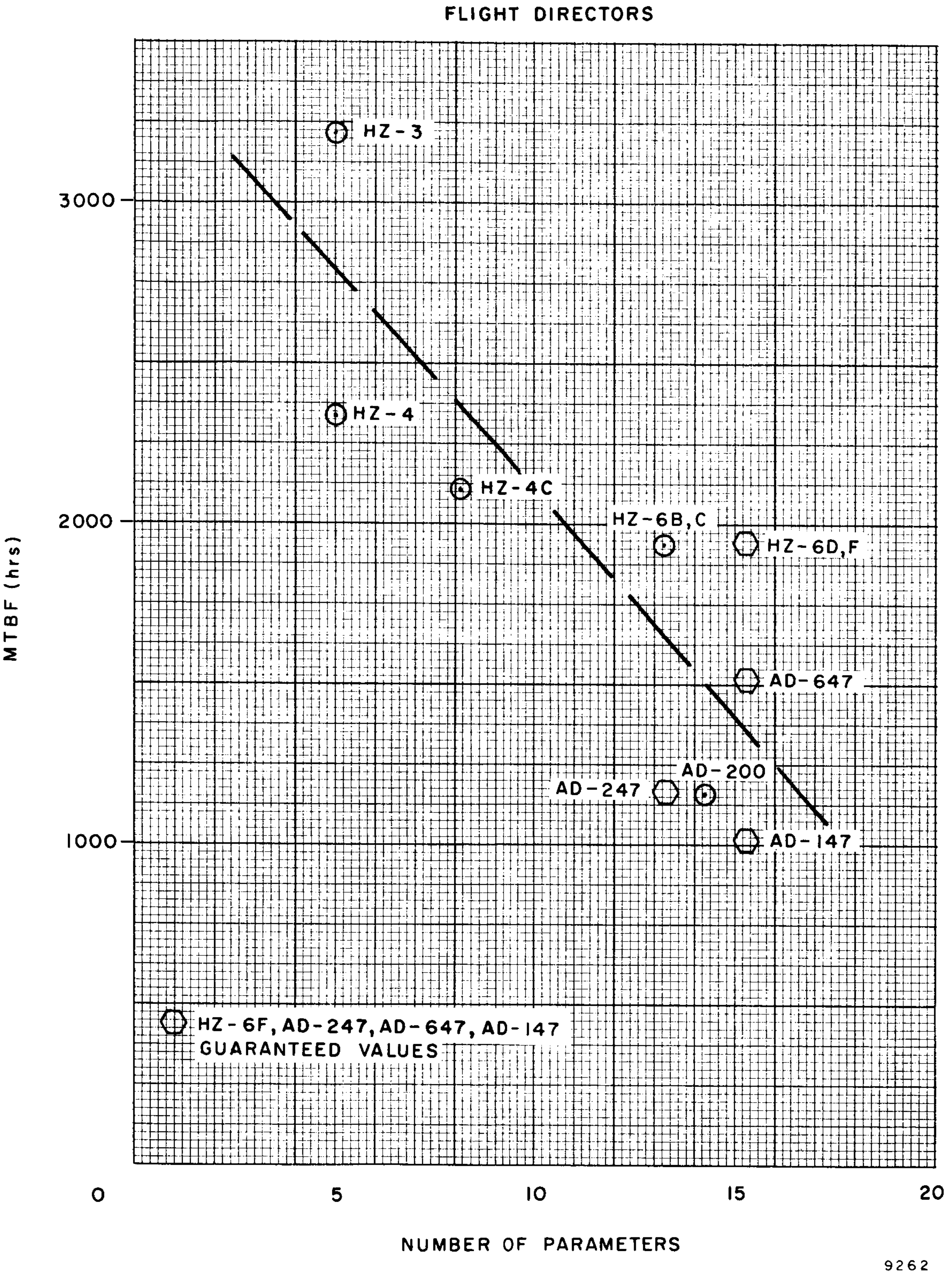

Figure 3-10
Trend of MTBF with Increased Sophistication of Attitude Director Indicator

information to other subsystems. A typical HSI is illustrated in figure 3-11. This particular indicator is not the most complex of HSI's now in use, but it is fairly representative of a modern HSI. Some units include course and heading set knobs on the indicator, but in the device shown in figure 3-11; these functions are set remotely. The synchro and resolver data for these functions, however, are generated within the indicators so that they are performing a signal processing and computing function as well as displaying aircraft position and orientation. Note that the DME readouts shown in figure 3-11 do not represent distance to touchdown. Also, it may be observed that the presentation of glide slope deviation on this indicator is not compatible with the concept of a horizontal situation display. Both lateral and vertical ILS deviations are displayed since this indicator has evolved from the type of device that traditionally provided the crosspointer radio deviation information. As in the case of the VSD's, these indicators are near their saturation point in terms of information that can be displayed by electromechanical means. Thus, future improvements are expected to be achieved with the use of all electronic displays.

4. CRT Pictorial Displays

During the 1950's, under US Navy sponsorship, developments were initiated to realize the possibility of producing a display that coincides with a real world view in terms of size, shape, motion parallax, perspective, and texture. This concept, usually associated with G. W. Hoover, was investigated and carried through various flight evaluations by Douglas Aircraft Company in the so-called Army-Navy Instrumentation Program (ANIP) for contact analog displays. The original intent was to develop a flat plate, transparent cathode ray tube (CRT) upon which all forward view information could be displayed. The pictorial representation of this information was to be generated by electronic computers and the resultant effect was to be that of a "highway in the sky". Kaiser Electronics built a flat transparent tube, and the system concept was flight tested several years ago. There have been a number of technical difficulties associated with this approach. A significant problem related to obtaining adequate contrast and visibility with the flat, transparent CRT. An alternate approach that does not attempt a heads-up capability alleviates much of this problem by not requiring a transparent tube. In this case, the display is presented on a normal CRT mounted in the instrument panel. It may be argued that this is a superior approach over collimated windscreen presentations in that accommodation of the eyes to close range is necessary for scanning other cockpit instrumentation.

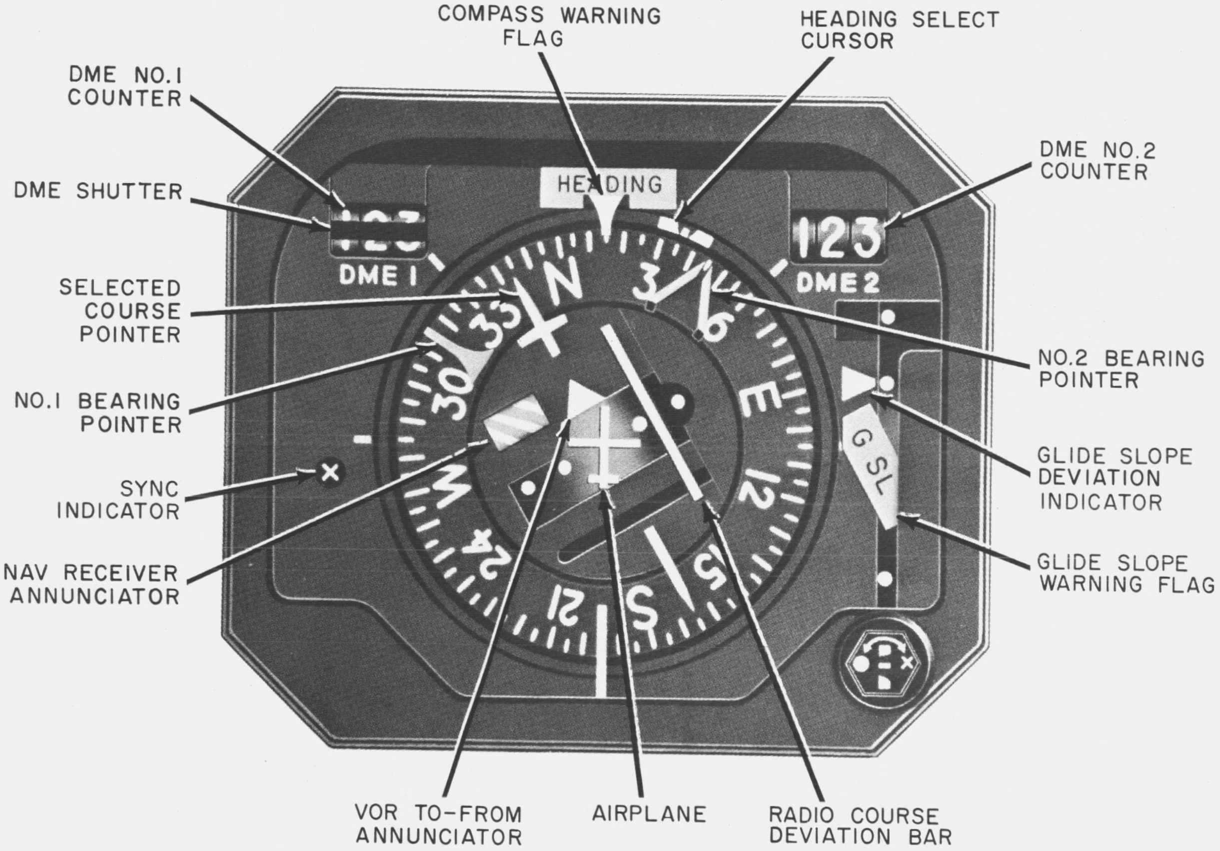

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Figure 3-11a
RD-201 Radio Direction Indicator

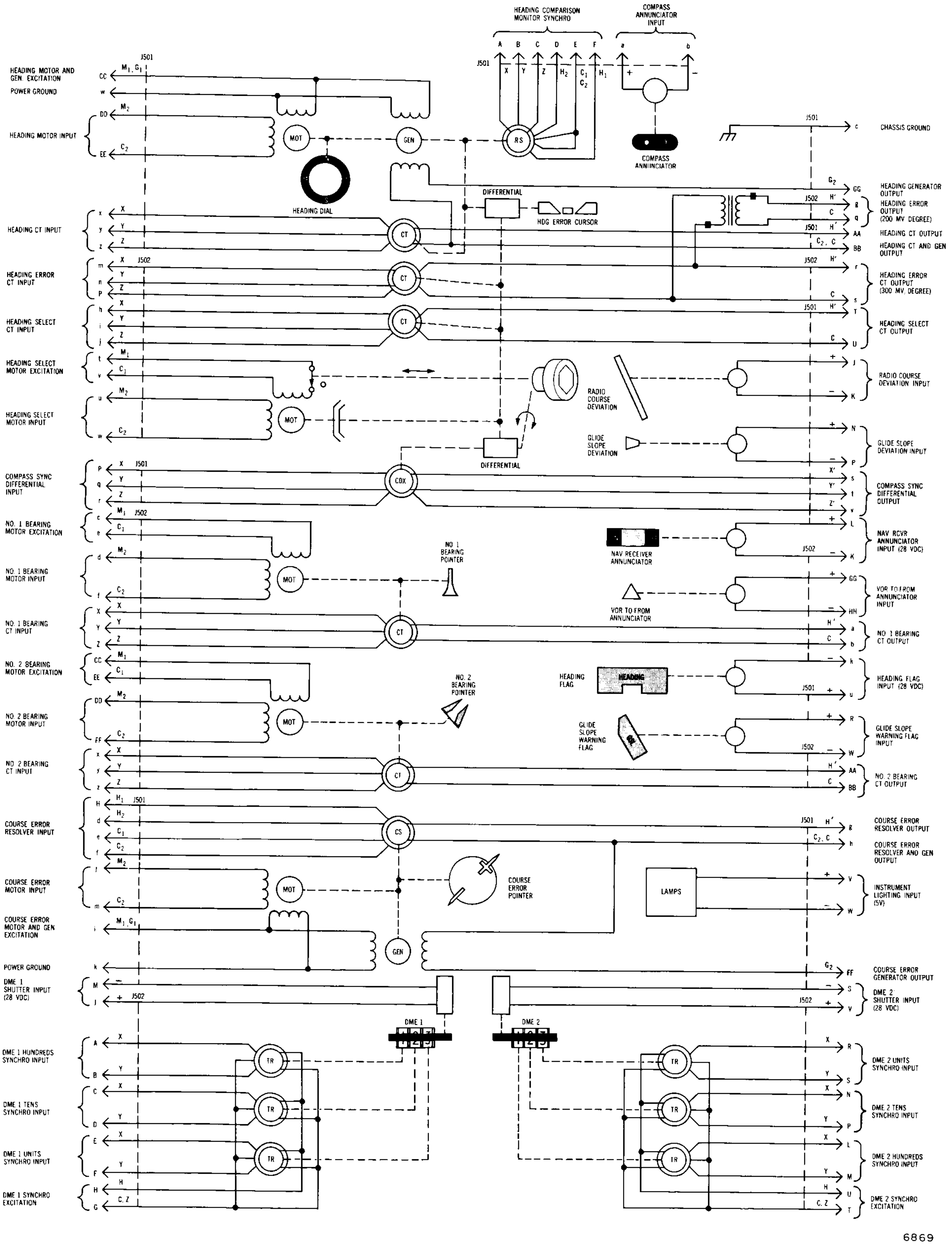


Figure 3-11b
Simplified Schematic Diagram (RD-201)

Various versions of CRT displays which fall into the heads-down category have been developed. The Kaiser FLITE-PATH display is used in the operational A6A aircraft. Figure 3-12 shows typical displays generated by this system.

A more sophisticated contact analog display that uses the large computing capacity of digital computers to generate the desired symbology is the GE contact analog display (reference 29). The system has the added versatility of a color CRT. Two typical pictorial flight control cues are shown in figure 3-13. While the capability of this system is greater than that of other present day contact analog systems that do not use a large digital computer complex to generate their displays, it is also far larger, more complex, more expensive, and hence less suitable for airborne applications. There are always the long-term projections that predict extraordinary price reductions for airborne digital computers. Perhaps in such an era, this type of system will ultimately find its application.

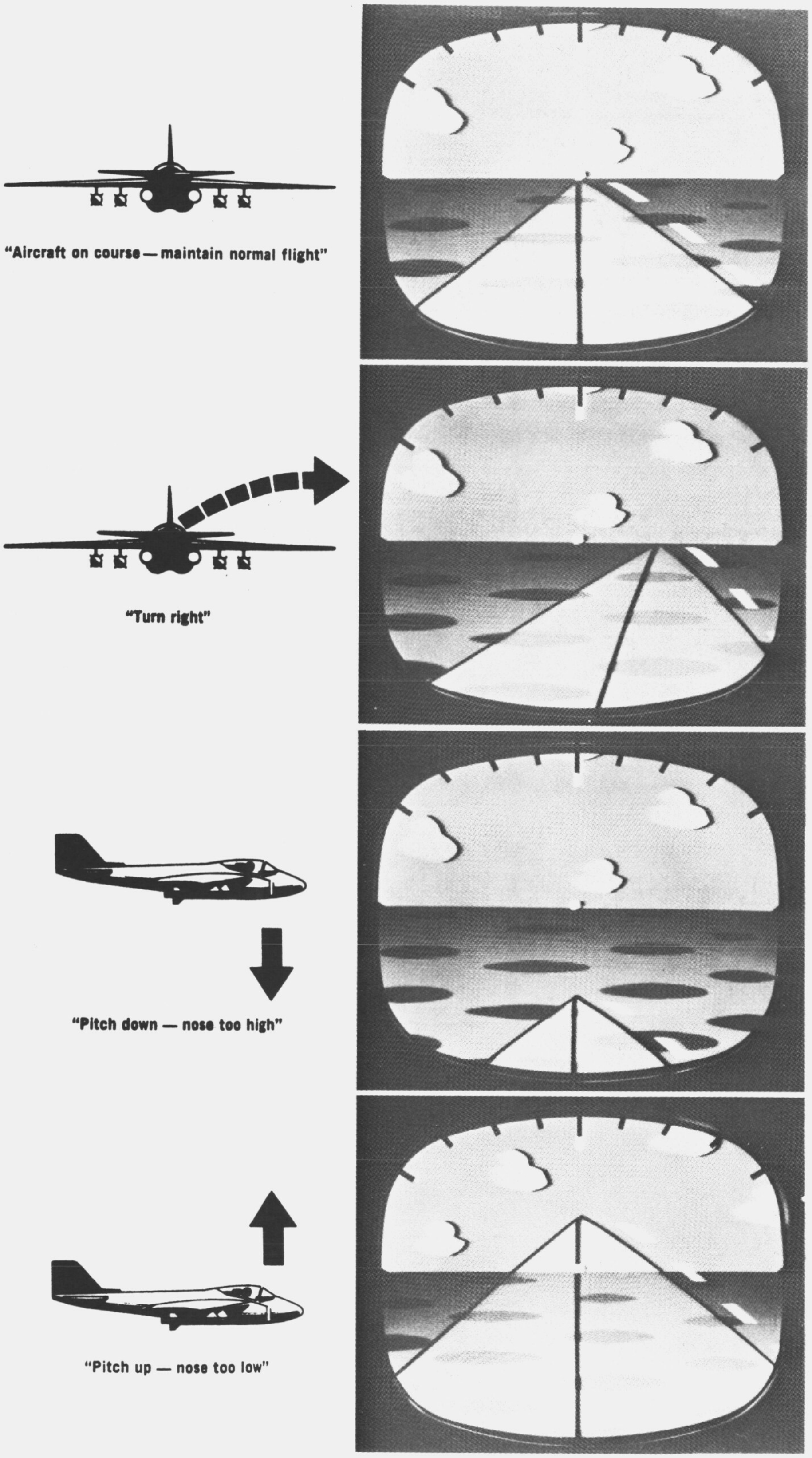
5. Heads-Up Displays

5.1 State of the Art

An excellent review of heads-up displays (HUD's) was given by Baxter and Workman at the 15th IATA Technical Conference (reference 30). There are many similarities in the various windscreen projection concepts which have been developed. In general, they include computers (analog), waveform generators, cathode ray tube, reticle, lens systems, combining surfaces, and stabilization system. The computers command various characters and symbols via the waveform generator which produces the CRT driving signals. A lens system collimates the CRT symbols as well as symbols reflected from the reticle so that they appear at optical infinity on the combining surface. That surface may be the windscreen or a transparent viewing area directly in front of the windscreen.

Three types of windscreen displays are shown here as representative of the state of the art. They are as follows:

- Spectron Display (reference 30), figure 3-14
- Sperry Display (an improvement over the version described in reference 30), figure 3-15
- Aeronautical Research Lab (APL) Display (reference 30), figure 3-16



Various commands are shown as they appear superimposed on the contact analog (attitude) display. If white command speed markers at right edge of pathway are moving towards pilot, speed should be decreased; conversely, if they are moving away, speed should be increased. If speed markers are not moving, the aircraft is travelling at prescribed command speed.

Figure 3-12
Typical Flight Path Displays

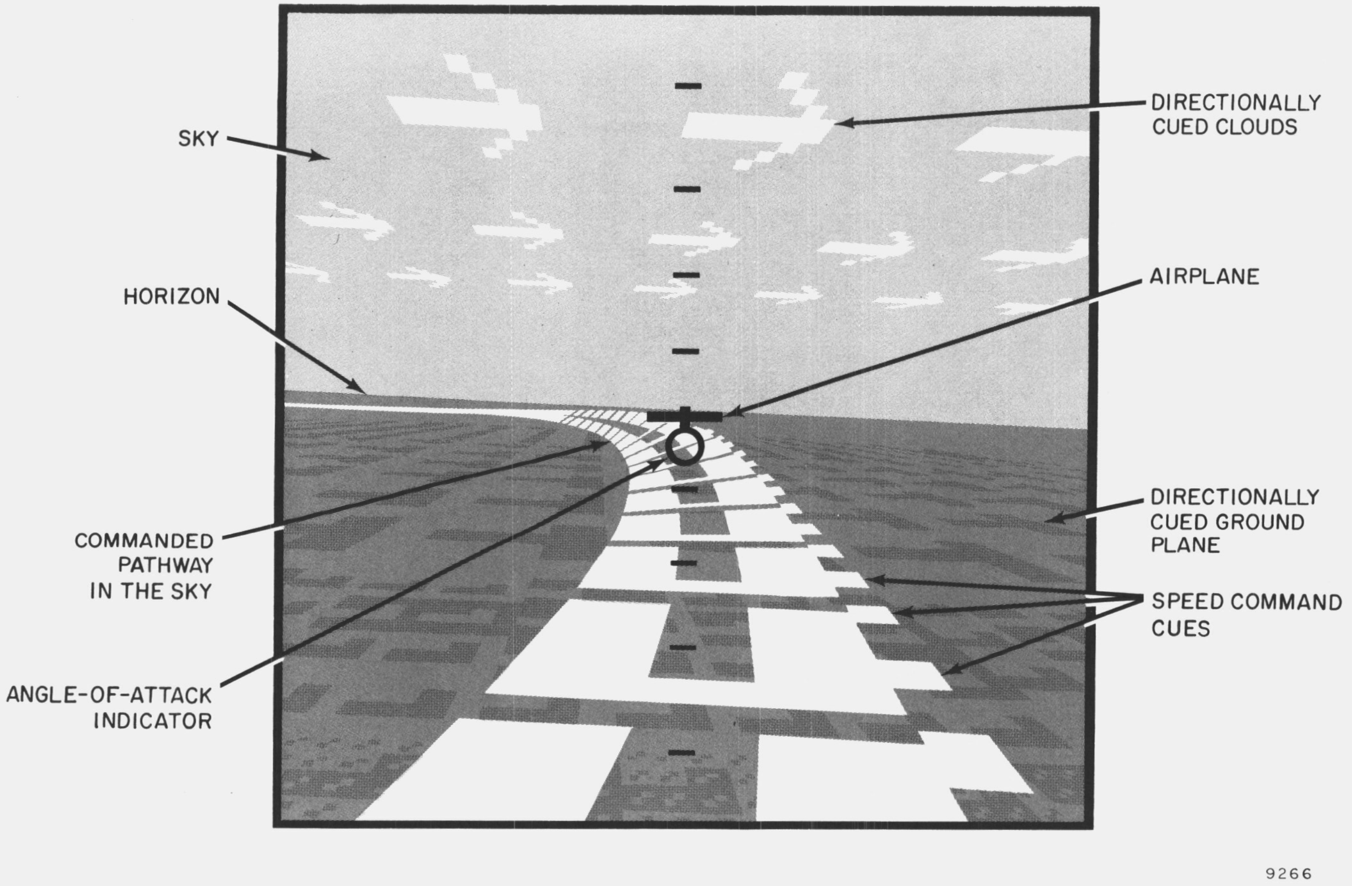


Figure 3-13a
In-Flight Showing Turn and Bank Command of Flight Path

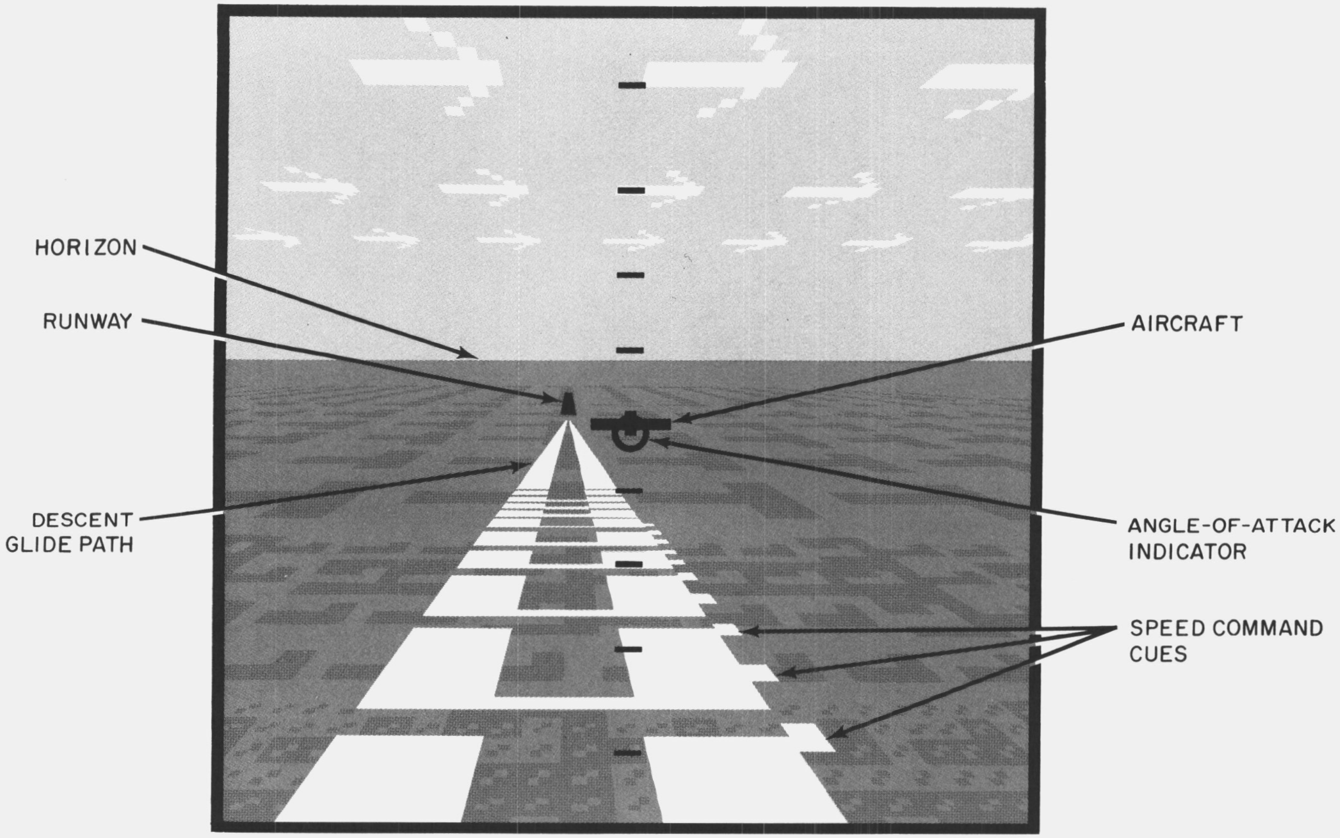


Figure 3-13b
Approach to Landing Showing Runway, and Flight Path Located
at Intersection of Glide Slope and Localizer

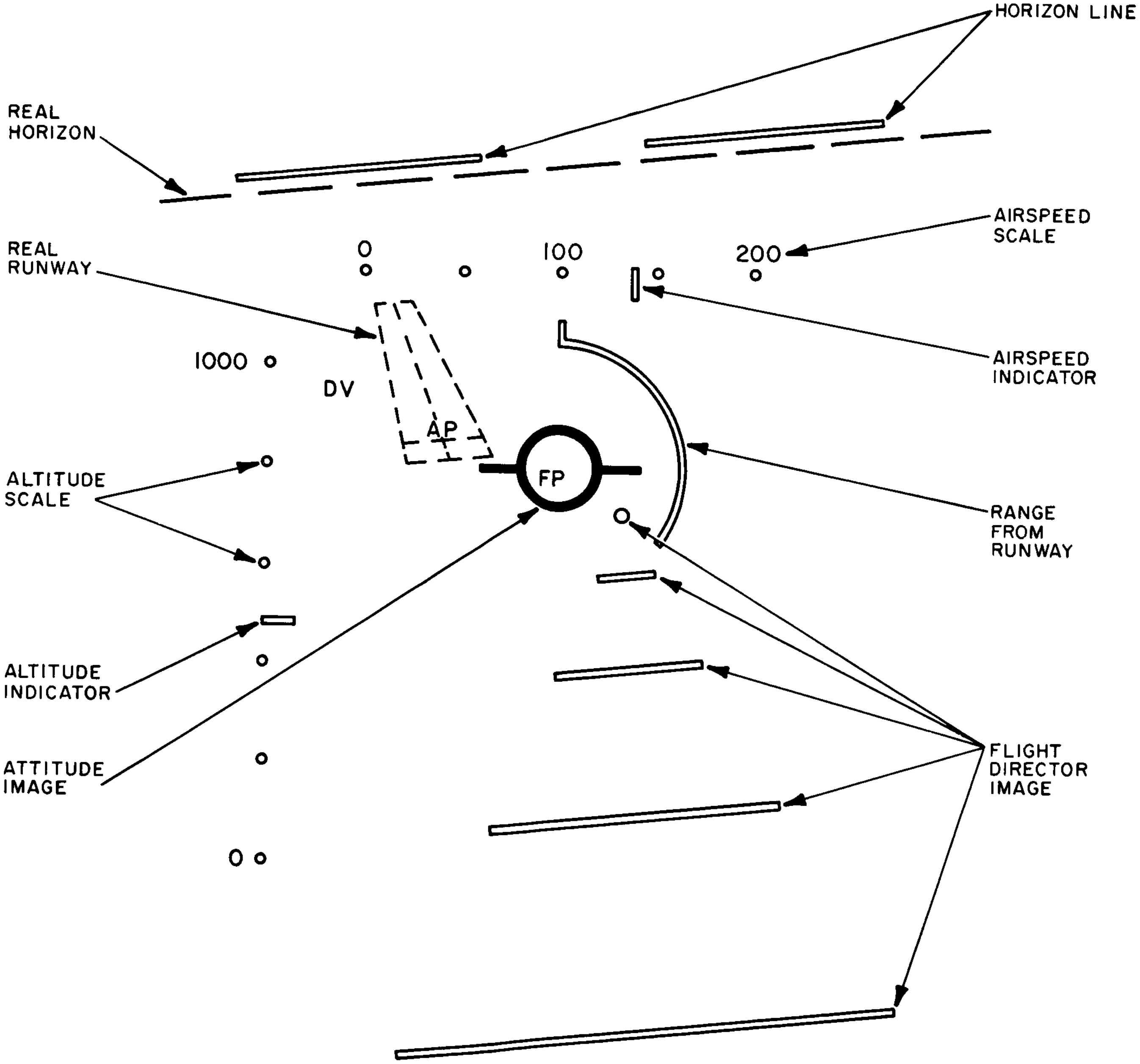


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Figure 3-14
The Spectron Display

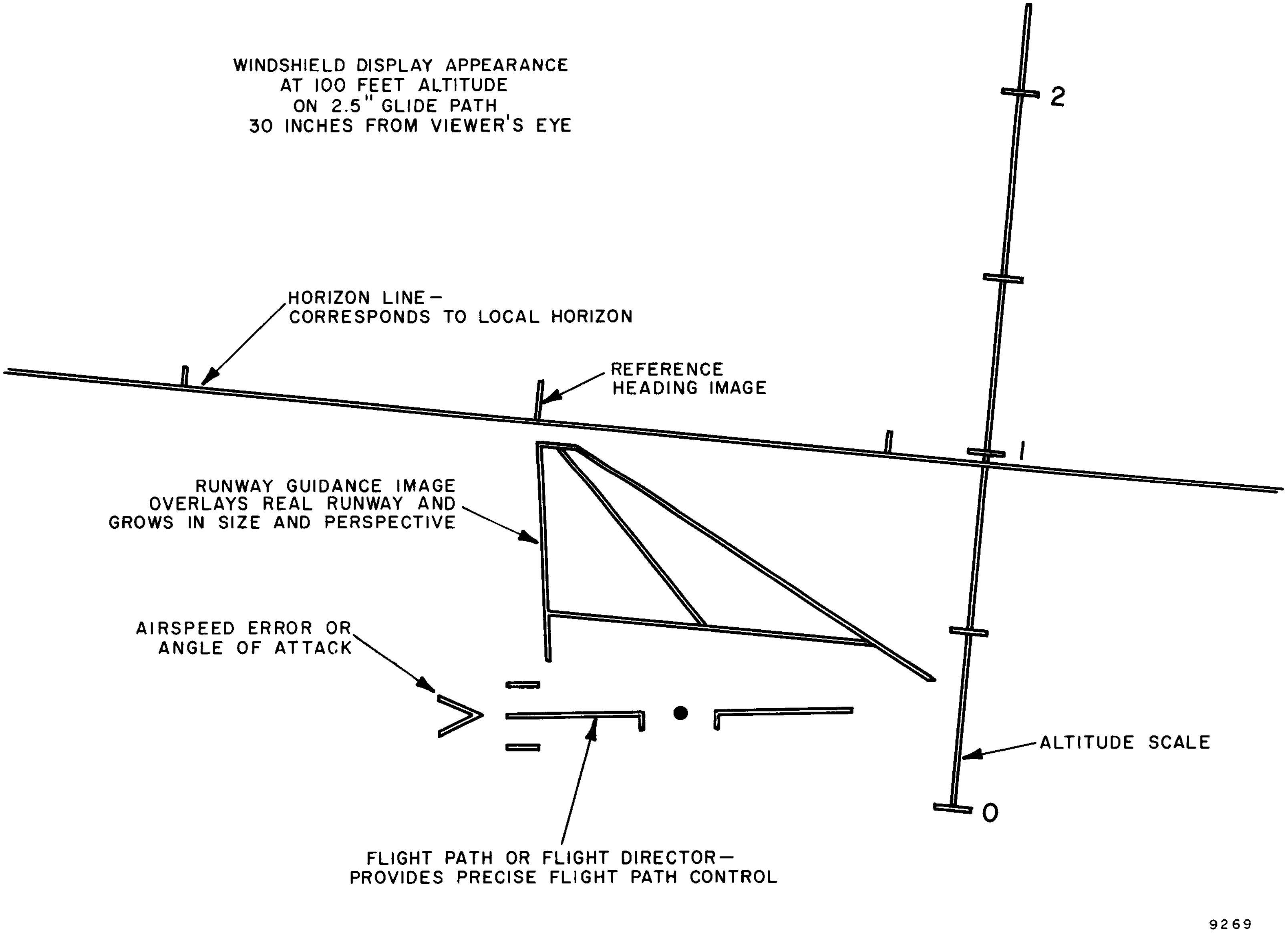

Figure 3-15
Sperry Heads-Up Display

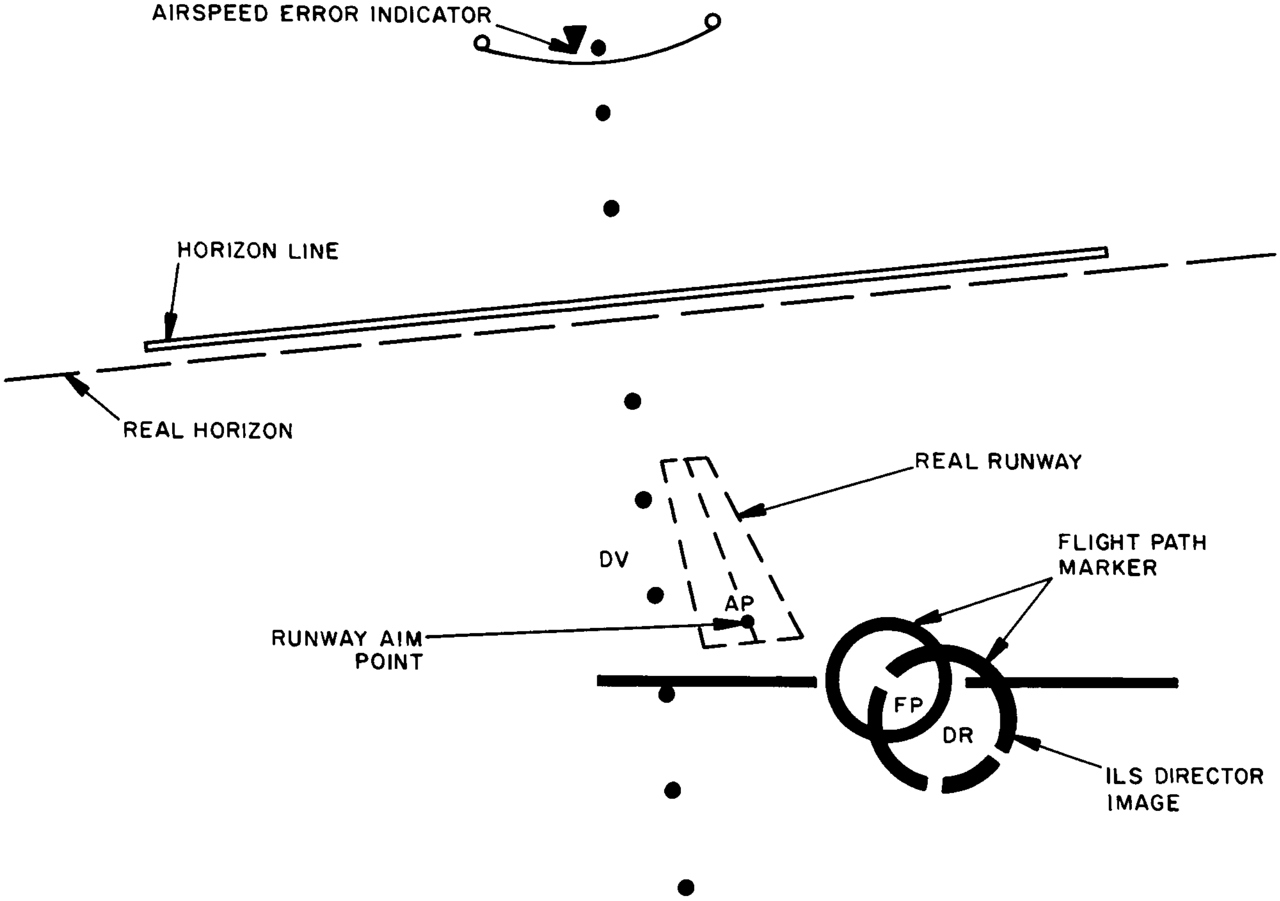

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Figure 3-16
The A. R. L. Display

5.2 Conclusions Concerning Heads-Up Displays

With all of the written articles, practical experience, and discussions on HUD's, a natural question to pose is, "Why aren't more HUD's seen flying in today's aircraft?"

There are a few good reasons why this has occurred. Pictorial displays for HUD application have been proposed that vary in function from the display of flight information to the display of raw sensor information. The presumed advantage of the HUD is that it allows the pilot to keep his head out of the cockpit during maneuvers close to the ground (low level flight and landing), thus facilitating the problem of transition from instrument to contact flight. This presumed advantage follows from two observed facts.

1) HUD's can be collimated, and thus the pilot does not have to change eye accommodation when shifting his gaze from the display to the outside world.
2) HUD's are in the normal line of sight the pilot uses during contact flight, thus reducing scan time.

Suppose, however, that one were simply to take information as it is presented on standard instrumentation and project it on the windscreen. The advantages of reduced scan time and reduced accommodation time would still remain with such a configuration, but is is extremely doubtful that this would represent a marked improvement in aircraft instrumentation.

Understandably enough, however, pictorial methods of encoding information have evolved concommitantly with the development of HUD displays. The real reason for the advantage of the HUD, if it turns out that there is one, may be not that the display is mounted in a see-through position over the panel but that the displayed information is encoded pictorially in an easily assimilated fashion.

Because pictorial HUD's replicate in the abstract certain features of the seen physical world, it is desirable that the symbols representing these features and the referent objects be in registry. If this requirement is met, then the HUD has the marked advantage of permitting the pilot to check the performance of the display system by matching display elements against their counterparts in the external world.

The brightness and form of the symbols on a HUD must be chosen with considerable care, for if the symbols are too bright they constitute a veiling illuminance that would tend to obscure ground objects; and if they are similar in configuration to ground patterns (runway lights, for example), they may cause confusion. Confusion may be preventable by intelligent choice of symbology and veiling may be avoided by manual or automatic control of display brightness.

A more serious problem arises from the necessity of placing the HUD over the instrument panel of the aircraft coupled with the limited field of view of most HUD devices. In a collimated HUD display where the presentation is to be in registry with the external environment, the cockpit geometry may not allow the pilot to see what he wants to see (for example, the outside runway) precisely at the time when the reason for using the HUD in the first place occurs. When the display magnification is unity and the angle of attack is large, in many aircraft all pertinent information disappears off the bottom of the display because of the limited field of view of the display. If the image is compressed (magnification < unity), then the symbols in the HUD will be markedly out of registry with objects in the real world. The effects of this are not completely known, but one hesitates to suggest a departure from unit magnification without empirical evidence.

The effects of small registry errors in collimated displays are deemed minor because in attempting a transition, the display symbols will be used by the pilot to tell him where to look. If he is not attempting a transition and flying the HUD, misregistration will not matter. If the image is not collimated, then serious misregistration problems would ensue; and it would be necessary to pick off signals from the pilot's head position to correct the display image. This is not envisioned as a serious issue since collimation appears to be an adequate yet simple solution.

It appears that the heads-up concept has not gained more favor with operators of today's aircraft for the following six reasons:

1) System cost
2) Optical problems
3) System reliability
4) Pilot acceptance
5) Dependence upon additional (or improved) ground navigation aids
6) Cockpit installation problems (retrofit)

The "ball park" cost figures for a typical HUD in prototype quantities is on the order of $100,000. This is considered by many to be too high for the function performed by a HUD at the present level of AWL capabilities.

Various optical problems involving the sight head have been encountered by groups developing this type of equipment.

Reliability of the electronics, the CRT, and various parts of the optical system has been a problem. Certainly the reliability of CRT's and electronics devices is improving steadily, and it must be assumed that proper development of new optical devices and techniques will simplify the HUD optics to a point that the overall reliability of the device will not be affected by the optics.

One big factor which used to be a problem appears to be that of pilot acceptance of the HUD technique. However, pilots who have flown HUD-directed approaches are enthusiastic about that system's capabilities, so it is assumed that this consideration will help the overall effectiveness of HUD in the future.

Most HUD systems derive at least part of their display from existing ILS signals. Some questions remain regarding the accuracy of the localizer at the runway threshold and radio altimeter may not be a good source of height data because of terrain profile effects.

Perhaps the most important limitation that explains why there are not more HUD's in the air is in the cockpit installation requirements. It appears that current jet cockpits are so crowded, and have so little room for expansion, that it would be practically impossible to retrofit HUD in them. Any permanent projection screen has to be ruled out. A foldup or folddown visor-type screen is possible, as is a rollup or rolldown window shade-type screen. But this only solves half of the problem. There still is not room for the sight head or projection system.

Spare headroom is sparse in these cockpits, so a mounting above or behind the pilot is, in most cases, ruled out. A possible solution at the present time would be to make the pilot wear a helmet mounted, gunsight type projection system, but this approach would hardly meet with a happy response from the airline pilots.

In summary, therefore, the status of HUD's is such that the problems to be solved are mainly operational and philosophical. The electronic techniques are available today. The optical problems relate to the specific intallation. If adequate provision is made for the optics in aircraft during their design, these problems can be solved. The work remaining to be done is in the area of symbology, lighting, and defining the specific details of using the display in actual aircraft operations.

SECTION IV

TECHNOLOGY ASSESSMENT OF ELECTROMAGNETIC REFERENCE SYSTEMS AND DEVICES FOR ALL WEATHER LANDING APPLICATIONS

A. INTRODUCTION

Electromagnetic systems, by definition, encompass all techniques utilizing radiated data between the aircraft and ground to determine the aircraft's position. The purpose of this section is to provide a state-of-the-art review of electromagnetic reference systems which have application to all weather landing. Systems and devices which will be considered include those now in general operational use, those which have been developed and evaluated in recent years, and those which are being suggested as having future potential.

This survey is primarily concerned with the performance of the systems and devices as sensors; whether or not the performance goals are sufficient to satisfactorily perform all weather landings is a controls problem and is beyond the scope of this analysis. The general format of the survey will include an introduction of the particular subject usually stressing the history of development and use, a description of the principles of operation of the overall system and various subsystems, and an appraisal of performance, both present and future, including advantages, liabilities, and possible needs for technology advances or additional study warranted for the particular type of system.

Since there are numerous electromagnetic reference systems and devices, it is convenient to categorize them into a few arbitrary classifications. For purposes of this survey, these arbitrary classifications are: Instrument Landing System (ILS), Cooperative Ground Radar-Data Link Systems, Scanning Beam Landing Systems, Artificial Imaging Systems, and Navigational Aids (NAVAIDS) including Distance Measuring Equipment (DME) and radio altimeters.

B. INSTRUMENT LANDING SYSTEM (ILS)

1. Introduction

The Instrument Landing System (ILS) has been in operational use since 1940 and is now the world standard low approach navigational aid (NAVAID). It is only a low approach system as far as the vertical guidance is concerned, although the lateral guidance information is usable to touchdown and beyond. It is a fairly safe assumption that ILS, in one form or another, will be in operational use for many years to come and therefore should be given first consideration in an evaluation of all weather landing systems.

The history (references 31 and 32) and technical advancement (references 33 and 34) of ILS have been documented by many writers. It is significant that the basic system, originally adopted by the International Civil Aviation Organization in 1946, has continued to be maintained as a world standard with modifications to specifications and equipment largely concerned with more accurate definition and methods for adjustment of the equipment. The ultimate limit of ILS is largely defined by propagation phenomena associated with ground terrain and the ability of antenna technology to offset some of these propagation limitations. Many studies and experimental programs have been performed in these areas during recent years, and are likely to continue as the associated technologies also advance.

2. Principles of Operation (References 35 and 36)

The ILS system uses a radiation pattern of fixed beams of unequal intensities in the various directions about the radio station to describe a course. The equipment used to generate all courses in line with the centerline of the runway is called a localizer. The inclined plane the aircraft flies from some elevation to the touchdown point on the runway is called the glide slope. Since both ground-based and airborne equipments are involved, the ILS system consists of four subsystems: a) the ground-based localizer, b) the ground-based glide slope, c) the airborne localizer receiver, and d) the airborne glide slope receiver. These basic subsystems are usually augmented by various NAVAIDS such as ADF homers, marker beacons, distance measuring equipment (DME), and high intensity lighting and radar; however, such NAVAIDS are useful with any approach system and will be discussed separately.

a. The ILS Localizer Ground Station

The ILS localizer transmitter operates in the 108 to 112 MHz frequency band and is physically located beyond the back end and on the centerline of the instrumented runway. The ground-based localizer antenna is composed of several (usually 5 to 8) properly spaced, horizontally polarized individual antennas excited with RF carrier and 90- and 150-Hz carrier modulated, sideband components where amplitude and phase relationship are carefully adjusted to produce the desired directional pattern.

The two central units of an eight antenna localizer array are excited with an RF carrier which is moduated by 90- and 150-Hz tones plus identification signals and voice. The radiation pattern of these carrier antennas is not very directional and produces an essentially equal signal strength, bidirectional beam oriented along the runway centerline. The remaining six antennas are excited with 90- and 150-Hz sideband components so adjusted in phase and magnitude as to produce a highly directional radiation pattern with maximum signal intensity at a 10-degree angle on either side of the course line and a null on the course line. The sideband space patterns are such that the 90-Hz component is in phase and the 150-Hz component is out of phase with the carrier modulated components to the left of the runway centerline as viewed from the runway. This 90- and 150-Hz phase relationship is reversed on the other side of the runway. The patterns of an eight antenna localizer array are shown in figure 4-1.

Accordingly, an angular line of position (LOP) guidance system is formed such that the effective modulation of the total signal received at any point in space within the approach path area is equal to the algebraic sum of the modulation components contained in the two signals radiated to that point, as shown vectorially in figure 4-2.

The localizer radiation pattern inherently provides a reverse-sensed back course and also radiates considerable omnidirectional RF energy. Reflections of localizer signals into the approach path area produced by terrain, adjacent structures, and vehicles upset the balance of the directly radiated 90- and 150-Hz signals to produce a form of noise called course bends. Since the course bends are a function of the physical location of the localizer, it is said to exhibit siting errors.

It is often possible to obtain considerable smoothing of localizer course bends by the use of wire screens behind the localizer and/or large directional antenna arrays such as the FAA's 35.66-meter (117-foot) long, 195.58-centimeter (77-inch) deep, and 104.14-centimeter (41-inch) high waveguide antenna.

b. The ILS Glide Slope Ground Station

The ILS glide slope transmitting facility operates in the 329.3 to 335 MHz frequency band and may be adjusted to provide a single glidepath angle between the limits of 2 to 5 degrees. The glide slope facility is located near but to one side of the desired touchdown point of the instrumented runway and transmits on a frequency channel determined in accordance with a standardized localizer-glide slope ILS channel pairing plan.

Two types of ground-based ILS glide slope subsystems have been used and are identified as the equisignal type and the null-reference type in accordance with the technique employed to generate the glidepath. The null-referenced type has replaced the older equisignal type at FAA instrumented air fields, but both will be described since the equisignal type may be in use at some military

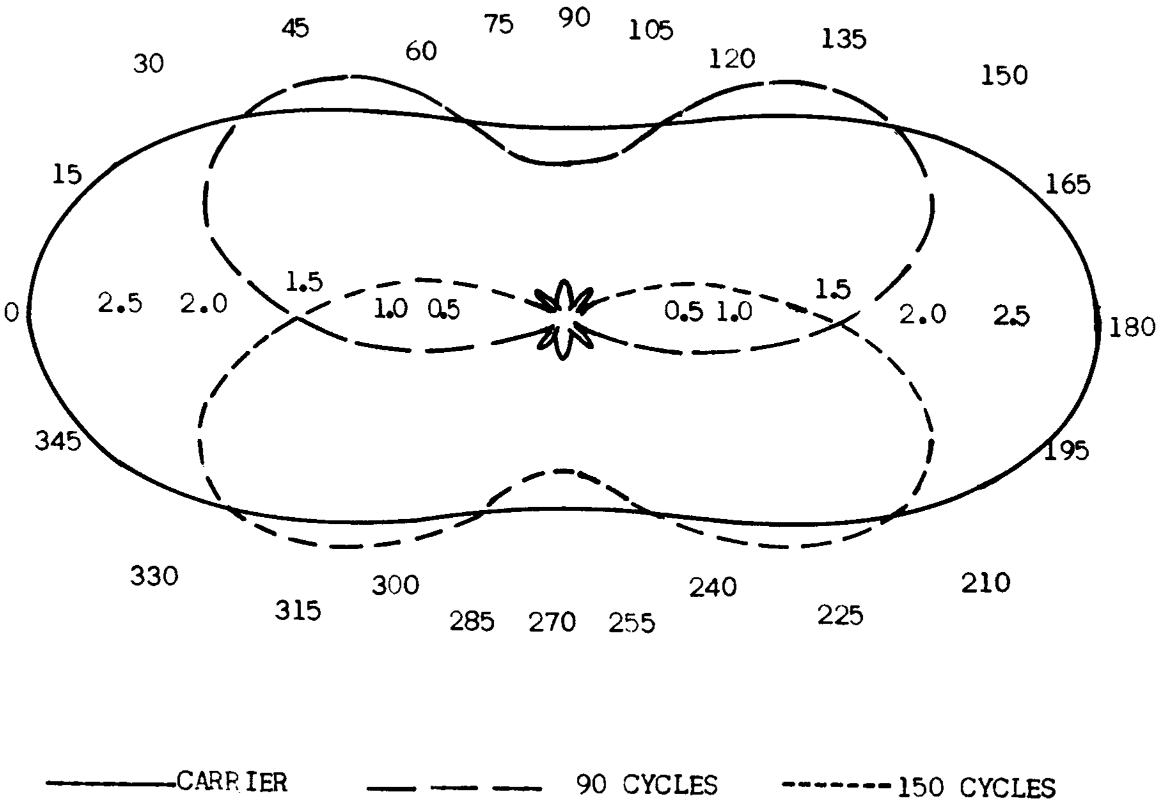

FIG. 4-1 -- Field Pattern of localizer developed by plotting the three patterns representing the 90-cycle signal, 150-cycle signal, the carrier frequency.

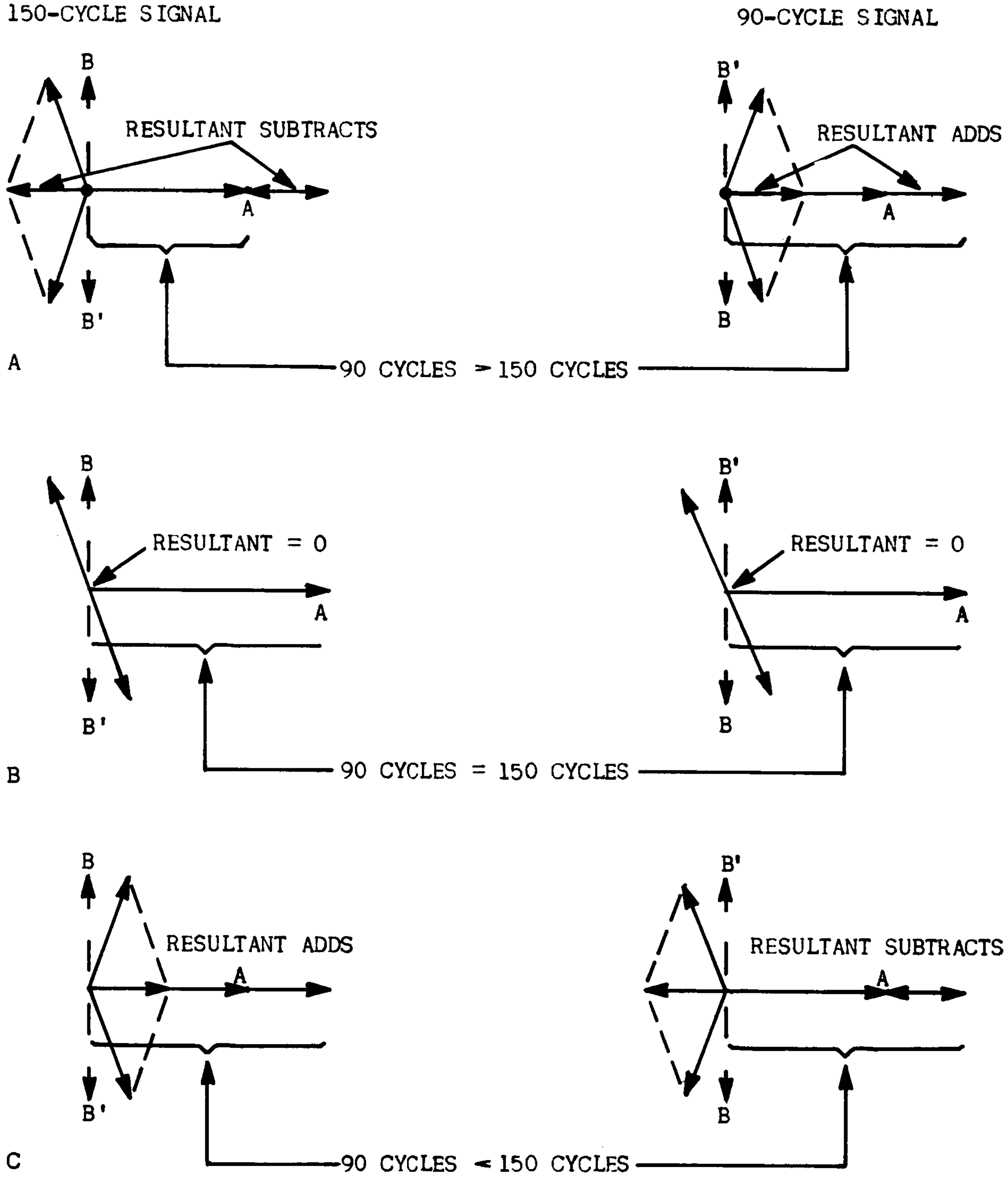

FIG. 4-2 -- Illustration of conditions at a point P for an equivalent three-element localizer antenna; A is the center antenna, B and B' are the end antennas. The sidebands of the 150-cycle signal from antenna B lag those from antenna A, while the 150-cycle sidebands from B' lead those in A. The resultants, therefore, subtract to produce a weakened 150-cycle signal. On the other hand, the sidebands of the 90-cycle signal from antenna B will be retarded in phase with respect to those from antenna A, while the 150-cycle sidebands from B' will lead those in A. The resultants, therefore, add to produce an increased 90-cycle signal, which greatly exceeds the 150-cycle signal. At B, is shown the conditions for a point located directly on a line passing through the central antenna and perpendicular through a line that joins the center of all antenna elements. At C, the conditions are for a point to the left of a line passing through antenna A and perpendicular through a line that joins the center of all antenna elements.

installations and/or carried in military inventories. Either type may be used without change in the airborne subsystem.

The equisignal glide slope uses an antenna array consisting of two horizontally polarized antennas mounted on a vertical mast directly above one another at heights above ground of about 1.83 and 8.53 meters (6 and 28 feet) for a 2-1/2 degree path angle. Path angle is a function of both antenna heights and the ratio of lower-antenna to upper-antenna signal strength.

The upper antenna of the equisignal type ILS glide slope radiates a 150-Hz modulated signal; however, ground reflections cause the maximum energy to be radiated at an elevation angle of approximately 1-3/4 degrees. The lower antenna radiates a 90-Hz signal and ground reflections cause the maximum signal strength to be obtained at an elevation angle of about 9 degrees. The relative amplitudes of the two antenna excitation signals are adjusted such that equal field strengths from the two antennas will be produced at an elevation angle of about 2-1/2 degrees.

The null-referenced type glide slope also uses two vertically mounted antennas but the above ground antenna heights for a 2-1/2 degree glide slope will be about 5.18 and 10.36 meters (17 and 34 feet). The field strength pattern produced by the directly radiated signal from the lower antenna plus the ground reflected signal produces a maximum at 2-1/2 and 7-1/2 degrees with a null at 5 degrees elevation angle. Likewise, the upper field strength pattern will exhibit a maximum at 1-1/4 and 3-3/4 degrees with a null at 2-1/2 degrees elevation angle.

The lower antenna of the null-referenced ILS glide slope is excited with 90- and 150-Hz modulated carrier energy and may be considered the reference signal. The upper antenna is excited with only 90- and 150-Hz sideband energy; however, ground reflections cause the 90-Hz component to be in phase and the 150-Hz component to be out of phase with the reference signal at elevation angles greater than the desired glidepath. The above described 90- and 150-Hz relationships are reversed below the glidepath.

The radiation pattern forms a vertical angle LOP guidance system in that the effective modulation of the total glide slope signal received at any point in space at low elevation angles within the approach path area is equal to the algebraic sum of the modulation components contained in the two signals radiated to that point. Both the equisignal and the null-reference types produce false glidepaths at high elevation angles; however, proper approach procedures effectively avoid these areas.

Since the descent path of the ILS glide slope subsystem is dependent on both the RF energy radiated directly from the antenna array and that which is reflected from the earth, a considerable area of flat terrain is required for the production of a straight glide slope. As the aircraft approaches the runway, the point of primary reflection on the ground also moves toward the runway. Consequently, surface undulations will produce a roughness in the glidepath. In addition, signal reflections from hills and other structures produce an alternating fly-up and fly-down signal called path scalloping. Path roughness and scalloping changes with vegetation coverage and surface modifications (for example, fencing, surface grading, transmission lines, etc) are such that recent pilot familiarization flights are desirable.

The null-reference glidepath angle is primarily a function of the upper antenna height. Snowfall or other temporary terrain characteristic changes do not affect the glidepath angle as much as was experienced with the equisignal type. In addition, the null-reference type provides greater linearity in glidepath displacement information.

Monitoring and ground checking of the glide slope function is a major problem. Glide slope checking involves vertical angles; and since the measurements must be made at a distance, the pickup must be elevated quite high to explore above and below the on-slope signal. Portable masts and balloons have been suggested; however, they cannot be kept in place permanently during all weather operations. A monitor of two pickup antennas on a pole approximately 67.06 meters (220 feet) in front of the glide slope array is ordinarily used to detect glide angle changes; however, such monitor detected changes are not always indicative of changes in that portion of the glidepath actually flown. Accordingly, periodic flight checks by a calibrated flight inspection aircraft is required to verify glide slope performance.

c. The ILS Airborne Subsystems

The ILS airborne subsystem consists of a localizer receiver, a glide slope receiver, and a frequency channel selector unit. The localizer and glide slope receivers are similar, except for the radio frequency sections, and are so interconnected that channel selection for both units is done in accordance with published localizer-glide slope frequency pairs.

Each receiver selectively filters the detected modulation components to form separate 90- and 150-Hz signals. The 90- and 150-Hz frequencies are rectified and are added to and subtracted from one another. The dc signal that is the sum of the rectified 90- and 150-Hz components is used to provide logic to inform using systems that the aircraft is within the beam confines. The dc signal that is the difference between the magnitudes of the rectified 90- and 150-Hz components is an analog voltage whose polarity is indicative of displacement direction and whose magnitude is proportional to the degree of displacement of the aircraft from the established path. The sensitivity of the localizer receiver is adjusted to provide a full scale fly-right or fly-left deflection with about a 3-degree angular displacement from the established path centerline. The glide slope receiver's sensitivity is adjusted to provide a full scale fly-up or fly-down deflection with a 0.5 degree angular displacement from the on-path course as established by the null-referenced type glide slope. A glide slope receiver adjusted for the above sensitivity, but used with an equisignal type ground unit, will give a full fly-down deflection for a 0.3-degree displacement; but a 0.5 degree displacement is required for a full fly-up indication.

3. Performance, Present and Future

It has been noted that ILS performance is greatly dependent upon local conditions of terrain, vegetation, and structural characteristics. These factors are inherently much more pronounced with glide slope than with localizer courses. In recent years, the use of highly directive localizer beam patterns, such as the FAA's 35.66-meter (117-foot) long slotted waveguide, have resulted in some localizer course accuracies of approximately 0.1 degree; however, available data is insufficient to determine if this is typical or an exceptional case. The antenna represents the largest portion of the size and weight of the ground equipment. The projected use of higher frequencies in the microwave spectrum could permit substantial reductions in the size and weight of the ground equipment and some improvement in the accuracy due to less susceptibility of microwave frequencies (when properly utilized) to multipath and other terrain interference phenomena. Thus, with proper design, implementation, and performance monitoring, it might be possible to approach localizer course accuracies of 0.01 degree at some sites.

The situation for ILS glide slope performance is not only poorer, but the prediction of ultimate performance is much more difficult to forecast. Based on pilot experience and some recordings of actual fixed glide slope approaches using theodolites, it is reasonable to expect fluctuations of as much as 0.25 degree and bias errors also of the order of 0.25 degree. Figure 4-3 (reference 38) shows typical glide slope bends at major US airports. In addition, the need for flat terrain forces the ILS glide slope transmitter to be located relatively far from the terminal end of the runway, and hence the need for more runway length between touchdown and the terminal end.

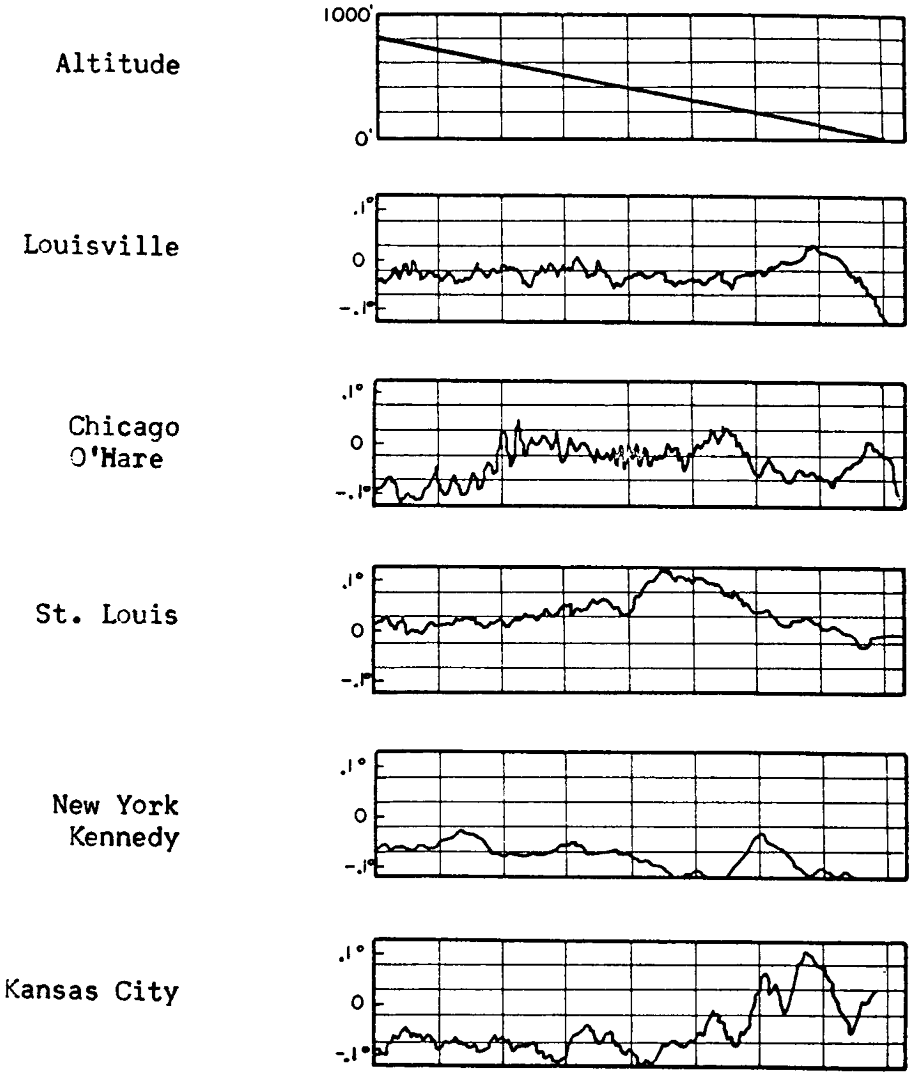

FIG. 4-3 -- Various Facility Bend Amplitude Characteristics

The use of more sophisticated vertical antenna arrays has demonstrated the ability to reduce these errors by a factor of 2 or better; however, greater reduction would require much larger vertical antenna arrays than might be considered practical. Thus, any significant improvement in glide slope accuracy must utilize higher frequencies in order to permit more sophisticated arrays of reduced size. Many of the proposed advanced glide slope systems are essentially narrow beam radars in the vertical plane, for which it is expected that accuracies of the order of 0.03 degree will be typical and 0.01 degree achievable under ideal terrain conditions.

The airborne ILS receiver technology appears to be leading the ground-based equipment technology. Solid-state ILS receivers offering improved reliability, self-test, and comparator warning were in a prototype stage over 3 years ago (reference 39). These receivers exhibited 3-sigma errors of:

	LOC	GS
On-course error, full environment	4.5 μa(5.0)*	5.6 μa(6.0)*
On-course error, limited environment	1.1 μa	1.5 μa
Off-course error, full environment	24 percent	18 percent
Off-course error, limited environment	6 percent	6 percent

where 150 μa represents full scale. Thus, on-course error in the realistic limited environment represent approximately 0.018 degree for localizer and 0.005 degree for glide slope.

C. COOPERATIVE GROUND RADAR - DATA LINK SYSTEMS

1. Introduction

Before considering some of the more advanced and elaborate methods of utilizing narrow microwave beams, it is convenient to consider the narrow beam microwave radar as a basic approach guidance technique. This approach is used in the Ground Controlled Approach (GCA), also called Precision Approach Radar (PAR), in which ground radar derived information is analyzed by a ground controller and instructions are verbally transmitted to the pilot by means of a radio communications link. Although GCA is presently limited to military operations, the use of a precision radar for monitoring is usually recommended for

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*ICAO Category II requirement. The ATA recommendations to the FAA as of December 14, 1966 specify the following receiver centering error for automatic landing systems:

LOC -- ±5 μa
GS -- ±10 μa

advanced approach guidance systems. A more elaborate method uses a data link to present ground radar information to the pilot for appropriate display such that the pilot acts directly on the information, thereby bypassing the ground controller.

2. Principles of Operation

The GCA system, which probably represents the simplest form of a ground-based radar system is composed of the following six units of equipment:

a) Azimuth scan antenna
b) Elevation scan antenna
c) Microwave (typically X-band) receiver-transmitter unit
d) Control and data display unit (including coordinate converter computer)
e) Ground-based radio communication subsystem
f) Airborne radio communication subsystem

These basic subsystems are usually augmented by corner-reflectors placed along the runway to facilitate calibration checks and adjustment of the GCA radar.

The GCA radar receiver-transmitter is time-shared between the two adjacently located scanning antennas to alternately measure azimuth and elevation position data in terms of angles and slant range. This radar unit is located at a position on the airfield to one side of the runway such that an unobstructed view of the approach area is provided but that the equipment will not be a flight obstruction.

The GCA radar video data is sent by cables to the control and data display unit or units located at the controllers' shelter. GCA radar data cable runs of 152.4 to 304.8 meters (500 to 1000 feet) are possible without additional amplification, and line amplifiers are available to permit remote location of the controllers' shelter up to 3048 meters (10,000 feet) from the radar site.

The GCA data indicator is known as the AZ-EL scope on which there are separate displays of azimuth-distance and elevation-distance information. The AZ-EL scope also displays electronically generated range marks and two curved cursor lines depicting the specified azimuth and glide approach paths.

GCA radar signals are appreciably attenuated during their required two-way passage through rain clouds or storms, and radar ranging capability through such atmospheric conditions suffers accordingly. Signal reflections from snow, rain, and clouds causes clutter on the AZ-EL scope that can mask appreciable areas of the display. The use of circular rather than linear polarization offers an appreciable improvement in the signal to clutter-noise ratio; however, it also reduces the effective range of the radar by 25 to 50 percent.

A GCA controller must be a skilled, quick-thinking individual and he requires frequent rest periods for safety reasons during prolonged periods of high density terminal area operations.

An automatic voice GCA system has been developed to relieve the controller of the routine task of verbal instructions although he is still retained as a monitor and operator. The automatic voice feature is obtained by the addition of GCA target trackers, computers and a multitrack magnetic drum recorder containing all the words, phrases, and sentences employed during a final approach talk down.

A cooperative system would include a beacon aboard the aircraft to increase range and reduce tracking error due to scintillation of the aircraft's apparent radar position. Since data is required, it is more conservative of spectrum utilization to employ a transponder in lieu of a beacon such that both tracking and data transmission can be accomplished with a single RF carrier band of frequencies.

3. Bell Automatic Landing Systems - AN/SPN-10, AN/GSN-5

The Bell Landing Systems use ground-based tracking radars in conjunction with ground-based computers, to generate steering commands that are transmitted to the aircraft. In the AN/GSN-5, which was a version of the built for the USAF, the transmission of commands to the aircraft was accomplished via the ILS receivers. The ground-computed steering commands were used to control the 90- and 150-Hz modulation of a carrier in such a manner that the ILS receivers could decode the signals as proportional steering commands. However, the system is designed primarily for use with various ground-to-air data links.

The important features of the Bell Landing Systems that are pertinent to this discussion are concerned with the tracking radar and position computation functions. There are strong philosophical objections to requiring the ground computer to develop the specific steering laws needed for each individual autopilot-aircraft combination. These steering laws must usually reflect certain subtleties of the aircraft control system, and it is easier to include the necessary compensations within the airborne equipment. Thus, it is in general more desirable to transmit position deviation signals to the aircraft. The elements of the Bell Landing System needed to generate this data are:

- K_a band tracking radar
- Position error computer
- Data link and encoders
- Airborne Beacon or corner reflector

The ground-based radar is a K_a band, conical scanning unit with high precision angle and range tracking circuits. The use of a 25.4-centimeter (10-inch) triangular corner reflector or a beacon, to avoid target scintillation radar tracking noise, is required on each aircraft.

A disadvantage of this system, in principle, is the limitation of the number of aircraft that can be accommodated simultaneously.

D. ADVANCED INTEGRATED LANDING SYSTEM

1. Introduction

The Airborne Instrument Laboratory system was selected by the FAA as the basis for developing what might be called a second generation All Weather Landing System. It uses narrow scanning microwave beams to supply accurate elevation and lateral guidance to touchdown. The new system, designated AILS for Advanced Integrated Landing System, was designed to be an integrated system in which complete landing guidance information is derived both in the aircraft and on the ground, thus providing an error monitoring capability. A proposed expansion to include a second vertical scanning beam would permit the derivation of aircraft elevation position from three combinations of data so that an error in any one data source could be detected during approach, and the landing completed using the other two sources.

2. Principles of Operation (Reference 40)

a. General Description

Figure 4-4 shows the basic elements of the landing guidance system. The two ground stations are not located at the same site; the azimuth site is located on the extended runway centerline at the stop end of the runway. The elevation site is located offset from the runway at a point some 304.8 to 457.2 meters (1000 to 1500 feet) behind the intended touchdown point. The DME transponder is located at the azimuth site; however, the system delay is adjusted to provide zero range at a point on the runway opposite the vertical scanner. This siting arrangement provides data, both in the aircraft and on the ground, in the most directly usable form.

One of the basic system requirements was to maintain a common reference for both air-derived and ground-derived data. This requirement was met by using the same scanning antenna for both beam guidance (air-derived) data transmission and the radar function. The microwave beam transmitted by this antenna bears a constant angular relationship to the antenna, and a precision angle data pickoff ensures an accurate knowledge of the pointing angle of the

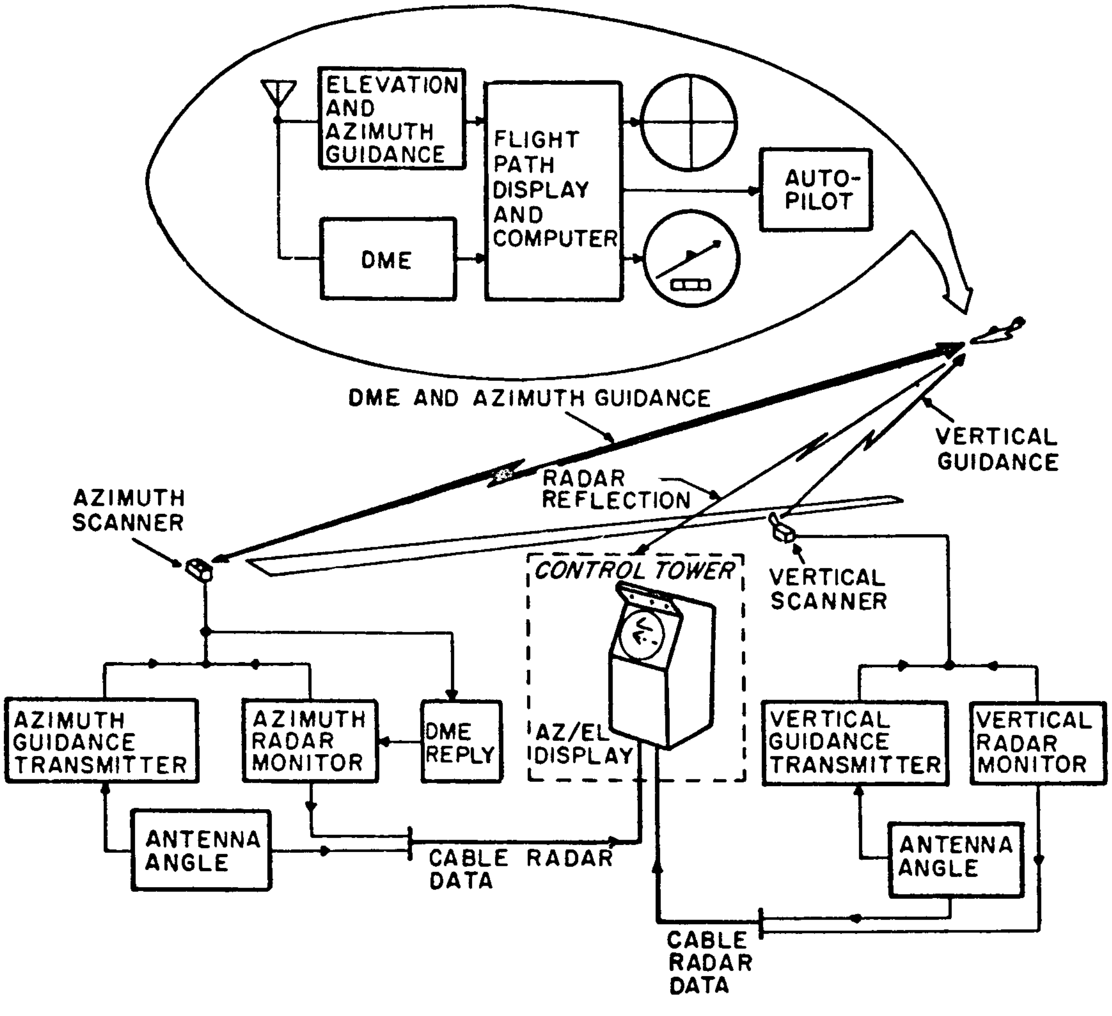


FIGURE 4-4. ELEMENTS OF LANDING GUIDANCE SYSTEM

antenna. This is an important aspect of the radar monitoring function in that the guidance information in the cockpit and on the ground controller's display have a common reference.

The requirement for using the same antenna for beam guidance and for radar imposed some definite restraints on the overall system design. The most important was the choice of mixing beam guidance and radar on a pulse-interlace basis or a scan-interlace basis.

Figure 4-5 shows the method of time-sharing the various functions. The time required for a complete antenna scan cycle is divided into six time periods. The antennas are made to mechanically scan well beyond the angles of active coverage (±11 degrees versus ±5 degrees of active coverage). The time during which one antenna is overscanning provides sufficient time for two other transmission periods. This scheme requires that the scanning antennas operate not only at the exact same frequency but at a fixed phase relationship.

The antenna (a thin pillbox design) is mounted on the end of a steel bar. Considering the other end of the steel bar fixed, if the antenna is rotated on the axis of the bar and quickly released, it will oscillate at a frequency determined by the spring constant of the steel bar and the moment of inertia of the antenna. The torsion bars are operated at a stress level that provides a large margin of safety from fatigue failure. A second torsion bar with an inertia model of the antenna can be used to cancel any forces on the cabinet from the fixed ends of the bars. Because the losses in the bearings and windage are small compared with the stored energy in the oscillating system, the Q of the oscillating system is very high. Little energy needs to be added to the oscillating system to keep it running, and the resonant frequency has been found to be stable over long time periods. The necessary energy is supplied by means of a magnetic torque motor that is excited in step with antenna motion to form a self-resonant system. A method of driving the scanner at its natural resonant frequency is necessary in order to take advantage of the low average energy or torque required to keep the resonant system running.

As previously mentioned, the landing system being developed must operate two such scanners in a fixed frequency and phase relationship. This is done by operating each scanner at its natural resonant frequency, as just described, and continuously tuning the resonant frequency of the elevation scanner to that of the azimuth scanner. This tuning is done by adjusting the position of weights on the antenna to control its moment of inertia. The amount of control adjustment necessary is determined by means of a phase lock sensing loop between the two antennas.

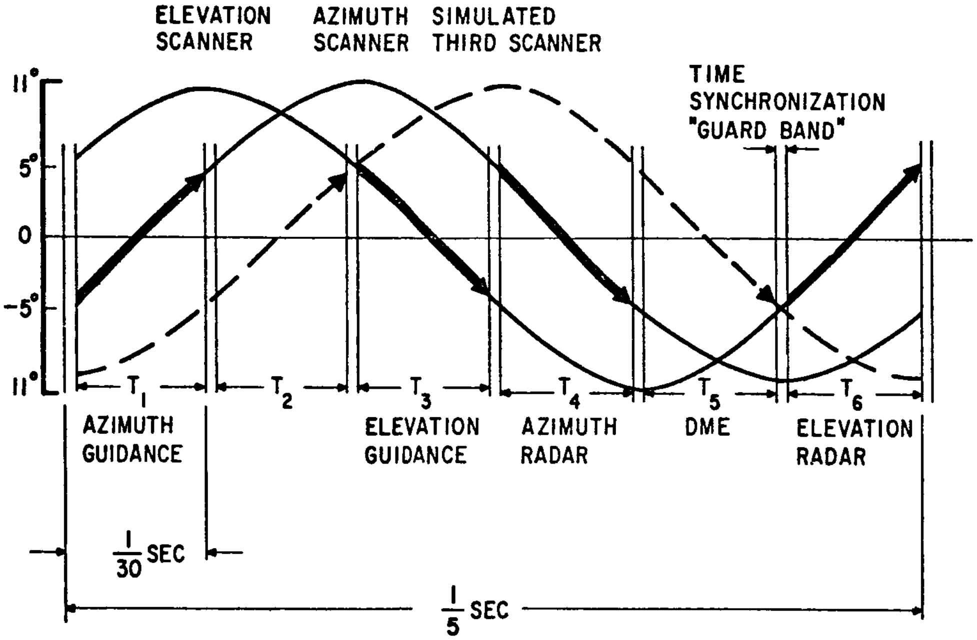


FIGURE 4-5. SCANNING AND TIMING CYCLE

b. Elevation and Azimuth Angle Data

The angle data transmission from the ground consists of a series of pulses, or pulse-pairs in this case, in which the spacing between the pulse groups represents the scan angle of the antenna at that instant. As shown in figure 4-6, 10 degrees of antenna scan is represented by a pulse-group spacing of from 40 to 120 microseconds. Thus, the pulse-group spacing has a variation of 80 microseconds to represent 10 degrees of antenna motion, or 8 microseconds per degree of change.

As the antenna scans, a photocell assembly scans an engraved scale attached to the antenna. The output of the photocell assembly is a pulse or mark for every 0.01 degree of movement of the antenna. A total of 1000-angle increment pulses are counted and stored in the angle data encoder. The function of the encoder is to translate the stored scan angle information into the variable spacing angle data code. By using a crystal oscillator as a precision timing reference, the output of the angle data encoder represents the instantaneous angle of the antenna to a design accuracy of ±0.01 degree.

As the encoded beam scans over an airborne receiver, the receiver must first decode identity to determine which function is being received. This decoding is accomplished on the sidelobe level or low skirts of the beam as the beam approaches the aircraft. This permits the receiver circuits to be set for the proper function and the proper AGC level to be established before angle data is taken from the beam. The angle decoder in the receiver decodes the angle message represented by each succeeding pulse group and determines the angle representing the peak of the beam by taking the center of gravity of the angle messages received.

The analog angle decoder circuit has a decoding range of 80 microseconds to encompass the full 10 degrees of beam data. Internal automatic calibrating circuits function between reception of the various beams to ensure that the angle data decoder is properly calibrated. The angle data received on each beam passage is used to update the appropriate memory so that continuously updated information is available for each function.

The same angle encoding and decoding technique is used in the azimuth or localizer scanner, except that the midpoint of the scan is used as the zero reference. In this case the angle memory provides a measure of deviation from the centerline of the runway, providing up to 5 degrees of fly-right or fly-left guidance.

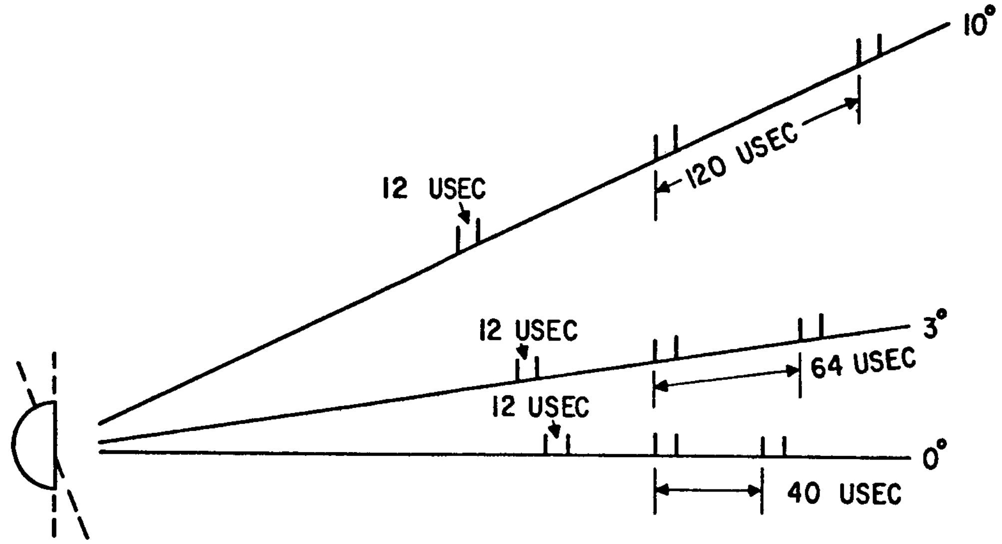


FIGURE 4-6. ELEVATION ANGLE DATA ENCODING

In order to optimize low angle coverage, the lowest angle of angle data transmission is selected by trial and error at each given site. Experience at several field sites has shown that a cutoff of transmission below approximately 0.1 degree is near optimum. In the azimuth scanner, angle data is again transmitted over the total angle of 10 degrees, or ±5 degrees from the centerline of the runway. Although a linear or proportional data coverage of ±5 degrees is adequate, additional angular coverage is needed to inform the pilot that he is off course to the right or to the left of the centerline. This clearance coverage is specified in ICAO specification to extend to 35 degrees on either side of the centerline. This coverage is provided in the present system by means of transmission from two nonscanning antennas. A short transmission of approximately 3 milliseconds (equivalent to the dwell time of a scanning beam on an aircraft) is transmitted from each of these nonscanning antennas in sequence. One of these transmissions is sent just before and the other just after the active scan of aximuth beam guidance.

To an aircraft flying in the clearance coverage of the system, these short transmissions will be interpreted in the same way as a beam transmission. The data transmitted in each clearance beam will be interpreted by a receiver located within that clearance area as an angle greater than 5 degrees on the appropriate side of the centerline. The signal level required in the coverage area must be great enough to overpower side lobe energy from the scanning antenna, but not strong enough to overpower the main beam of the scanning antenna. Because the clearance antenna has about 1 percent of the gain of the scanning antenna, the power level used to transmit beam guidance over the scanning antenna is not sufficient to transmit the clearance signal. The required signal level for clearance transmission is obtained by using the high-powered radar transmitter for this purpose. Thus the ratio of antenna gains between beam guidance and clearance transmission is offset by the ratio of transmitter powers between beam guidance transmitter and radar transmitter.

The airborne antenna is mounted behind the weather radar radome. Actually the only requirement for locating the receiving antenna is that it be placed relatively high on the aircraft and have an unobstructed forward view. The required antenna is small, having a frontal area of about 2.54 square centimeters (1 square inch); and it does not represent a serious drag problem if mounted protruding through the skin of the aircraft, except possibly for SST aircraft.

The airborne equipment (shown in figure 4-7) uses a superheterodyne receiver. A crystal-controlled,solid-state local oscillator source ensures receiver frequency stability. The frequency of the local oscillator can be switched to any one of ten available channels.

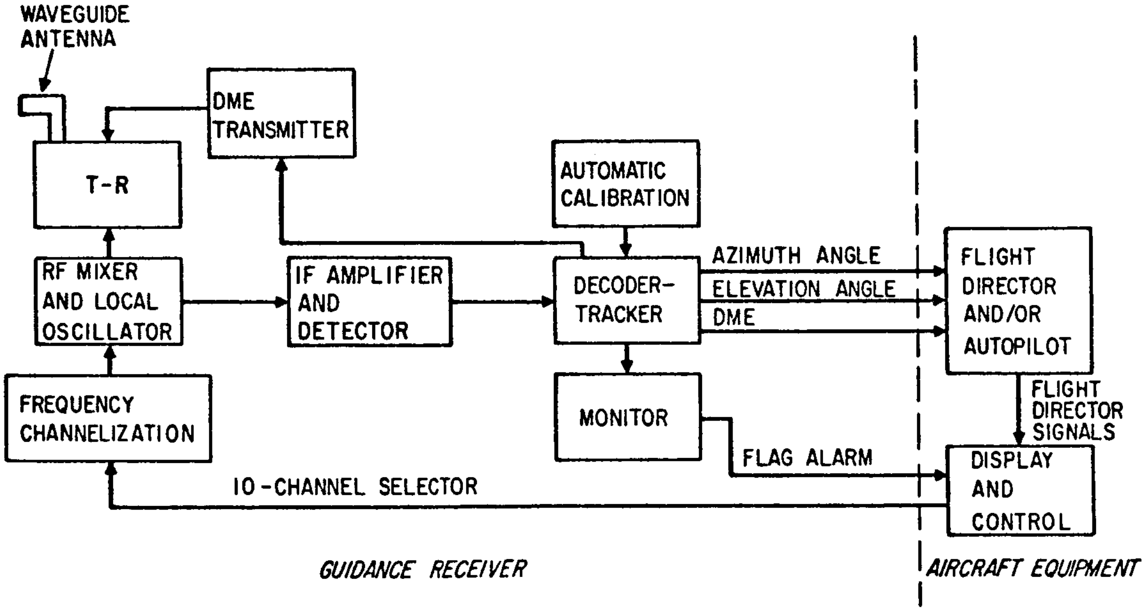


FIGURE 4-7. SIMPLIFIED BLOCK DIAGRAM OF AIRBORNE EQUIPMENT

The received angle data is processed in the decoder-tracker and stored in an appropriate output memory for use by the flight director or autopilot. The decoder-tracker performs the tasks of sorting out or decoding the function being received, decoding the angle data code, and determining the angle representing the peak of the beam as it passes over the aircraft. The angle data decoder uses a linear sawtooth waveform that is initiated after each pulse and momentarily clamped and sampled upon reception of the next pulse. The voltage level reached by the sawtooth waveform is a measure of the time between pulses. These voltage samples are compared with the angle memory voltage; the resultant error signals are averaged over the beam and applied to correct the memory to the new angle value. The decoder-tracker circuits are used in turn for the two angles and, as explained later, for the DME function. After each beam has been received, the decoder-tracker circuits are automatically cycled through an interval calibration routine. For this purpose, a crystal-oscillator timing standard is used to generate a test beam signal that is processed by the decoder-tracker, and the decoder is servoed to produce the correct output. The automatic calibration is alternately performed at an angle of 0 degrees (to control the start of the sawtooth waveform) and at an angle of 5 degrees (to control the sawtooth slope). This automatic calibration makes possible the use of a simple analog decoder to obtain the precision decoding required.

c. Distance Measurement

Associated with the air-derived angular guidance is a precision distance measuring system. The distance of the aircraft from a selected point on the runway is determined in the usual way by measuring the time required for a pulse to travel from an airborne interrogator to a ground transponder and back to the aircraft. Fortunately, the most critical portion, the measurement of time delay, can be accomplished by the angle data decoder with ample accuracy. In the AILS, the DME transponder is placed at the azimuth scanner site because the distance to a point on the runway could be measured directly without having to compensate for the slant range error that would result from an offset site. An autocalibration technique is used to continuously correct the delay time of the transponder to minimize error.

d. Ground-Derived Guidance

Ground-derived guidance is provided from both the elevation and azimuth ground sites by radar skin tracking. The radar function, as stated earlier, is time-shared on the scanning antenna at each site with the beam guidance function. This provides a radar data rate from each site of five samples per second. Other features of the radar are the use of circular polarization to minimize the effect of rain clutter, and MTI to minimize the effect of both rain and ground clutter. The radar data is displayed on a standard AZ-EL display for use by the traffic controllers. A radar transmitter is also used for the transmission of azimuth clearance guidance and DME transponder replies.

Both the elevation and azimuth scanning antennas are circularly polarized. The elevation antenna has a 0.5 degree half-power beamwidth in elevation and an azimuth-plane beamwidth of about 20 degrees. The azimuth site antenna also has a 0.5 degree beamwidth in the direction of scan, but has a shaped beam in the vertical plane. This is necessary for both radar and beam guidance to minimize the ground lobing and attendant nulls in the vertical coverage that would be present if significant energy were allowed to strike the ground. The primary pattern in elevation is about 3 degrees between half-power points, providing a sharp cutoff on the lower side of the pattern; it is tapered on the upper side to provide cosecant-squared coverage to at least 10 degrees.

The MTI that is incorporated into the radar design is a noncoherent system that uses double cancellation and has a staggered PRF to eliminate blind speeds in the range of interest. The precision angle data pickoff used for the beam guidance function will also be used to transmit angle data to the AZ-EL display. The angle increment pulses are sent to the display site, where they are counted and stored in a digital counter that is also used as a digital-to-analog converter. Thus a dc voltage that is accurately proportional to scan angle is available to drive the AZ-EL sweep circuits. Also available from the counter are precision angle pickoffs for generating angle marks on the display.

3. Performance, Present and Future

The AILS system operates at K_u band, between 15.4 and 15.7 GHz. At this frequency, beam guidance requirements can be met at ranges of over 24.14 kilometers (15 miles) with the transmitter peak power of 2 kw. A peak power of 100 kw is used for the skin-tracking radar and for the DME transponder. The airborne interrogator operates at a peak power level of 2 kw.

The system has been designed to provide elevation, azimuth, and range data as follows:

- To provide air-derived angular measurements accurate to within ±0.03 degree (one sigma) in both elevation and azimuth, making use of scanning microwave beams that transmit angle data with 0.01-degree precision at a sampling rate of 5 scans per second, from 0 to 10 degrees in elevation and over ±5 degrees from the runway centerline in azimuth (with extended clearance coverage), out to 24.14 kilometers (15 miles) from the runway threshold.

- To provide air-derived distance measurement accurate to within the greater of 30.48 meters (100 feet) or 1 percent making use of an airborne interrogator and ground-based transponder, from the runway to a distance of 24.14 kilometers (15 miles).

Major consideration for improving or extending the capabilities include the addition of a second elevation beam guidance site (for monitoring redundancy) and the incorporation of the DME interrogator-transmitter link into the ground radar system in order to eliminate scintillation, or angle jitter, due to skin tracking so as to improve the tracking accuracy at short ranges.

The ground equipment is more complex than for the conventional ILS system. The airborne equipment is also more complex than the associated airborne equipment of the ILS system, partially due to increased data decoding required by the AILS system and substantially due to the addition of a precision DME transmitter, which would be a valuable feature for an ILS system also. At this time, the AILS system is being evaluated as to accuracy using a probing technique.

E. ARTIFICIAL IMAGING SYSTEMS

1. Introduction

The Bendix Microvision and the Sperry Beacon Vision systems provide an artificial image of the runway during landings under any visibility conditions. When used with a windshield display, a series of data points outlining the runway is generated, producing an image analogous to the visual image the pilot ordinarily sees in clear visibility landings. The artificial image is superimposed on the visual image (when present), independent of motion of the pilot's head and aircraft maneuvers.

There are two distinct technologies associated with this type of system; one technology is associated with the electromagnetic propagation and sensor, the other technology is associated with the display. Of the two, the latter is probably the most complex and subject to controversy; and the success or failure of this type of system will probably depend more on the display concepts than on the sensing techniques. Thus, it is difficult to make a realistic comparison of this type system with the other systems already described. The discussion to follow will concentrate almost entirely upon the sensor aspects of an artificial imaging system.

2. Principles of Operation

The following system description will apply to the Sperry Beacon Vision system (reference 41) and then be followed by a comparison of the significant differences of the Bendix Microvision system. The Sperry system employs a set of sequentially switched beacons placed on the edges of the runway and an airborne electronic track monopulse receiver to determine the angular positions of the beacons relative to the airplane's axes. No stabilization is employed in the receiving antenna since the effects of airplane maneuvers must be retained in a realistic display. Also, range is not measured because the pilot normally estimates range from visual angular information and knowledge of runway dimensions.

The beacons are programmed to radiate sequentially, and the frame time for one complete cycle around the perimeter of the runway is short enough to give the illusion of simultaneous tracking of all beacons, so that there is a continuous display of the artificial image of the runway.

The airborne microwave sensor consists of a monopulse tracking system using phase comparison rather than amplitude comparison. The phase information is derived from two pairs of antennas; one pair of antennas is used for elevation sensing, the other pair of antennas is used for azimuth tracking. For two identical antennas of known spacing, the phase difference between the signals received at the antennas is a function of the angle of arrival of the microwave energy, which is defined by the well-known phase interferometer equation.

$$\phi = (2\pi d/\lambda) \sin \beta \qquad (4\text{-}1)$$

where

ϕ = phase difference

d = antenna spacing

λ = wavelength

β = angle of arrival with respect to the perpendicular bisector of the line connecting the two antennas

Either open loop or closed loop tracking can be employed. Microvision uses open loop tracking whereby each signal is procured in its respective receiver and the phase difference is measured at video frequencies. The advantage is simplicity; the disadvantage is susceptibility to differential phase drift in the two channels and varying phase characteristic of the comparator circuits. Beacon Vision uses closed loop tracking whereby an unbalance in phase is compensated by a phase shifter in one or both of the RF channels. The advantage is less susceptibility to calibration drifts; the disadvantage is increased complexity imposed by the closed loop system which must necessarily be very fast acting because of the rapid sequencing of the ground beacons. Ferrite phase shifters are used as the controlling elements. An alternative approach, not used in either of the two systems discussed, is the application of closed loop control with a variable attenuator to effect a balance of phase. Attenuators are generally simpler than ferrite phase shifters, but require an attendant loss of signal power.

The phase difference is read out as the angle of arrival of the electromagnetic energy which, except for propagation anomalies, is the line of sight angular displacement of the respective beacon off the centerline of the antenna pair. Actually, this angular data is presented as x-y coordinate data corresponding to the elevation and the azimuth axes of the aircraft, regardless of the particular attitude of the aircraft at that instant. This data is provided to the display subsystem, which requires certain timing interfacing between the sensor and the display.

In general, the Microvision and the Beacon Vision sensing systems differ primarily in the following five aspects:

	Microvision		Beacon Vision
1.	Open loop, parallel channels	1.	Closed loop electronic scanning
2.	Crystal video	2.	Superheterodyne
3.	Unsynchronized free-running beacons	3.	Synchronized and sequenced beacons
4.	No anti-multipath provisions	4.	Short pulses, leading edge track
5.	High power beacons	5.	Medium power beacons

3. Performance, Present and Future

Quantitative data on the performance of these systems in regard to sensor performance are difficult to obtain since these systems are judged and evaluated subjectively, largely on the total system including display.

The accuracy of an airborne angle sensor need not be as high as that needed by ground-based radar landing systems. This results from the two dimensional perspective display effectively smoothing small aircraft position errors with the amount of smoothing increasing as the aircraft approaches the touchdown point. Most studies indicate that an angular accuracy of 0.1 degree is desired. The Beacon Vision prototype system demonstrated an ability to achieve 0.2 degree (3-sigma) accuracy. Some known improvement is available in better circuit components; however, it was determined that much of the remaining error is due to propagation anomalies. Considerable experimentation was undertaken to improve the latter by means of more judicious design of ground beacon antennas with regard to the patterns and their physical location.

The size and complexity of the airborne elements represent one of the most severe limitations of an artificial imaging system. Not only does the sensor require advanced microwave packaging technology in order to hold its size and weight to reasonable values, the airborne antenna requires a favorable position on the aircraft such as the aircraft nose, and the imaging subsystem represents considerable size and weight in the pilot's cockpit, an area already overcrowded with equipment.

The future of this type system probably will be determined by the attitude of pilots and responsible personnel to its philosophy. Although it represents to the pilot what might be considered the most natural form of guidance display, its acceptance is influenced by the controversies surrounding heads-up and heads-down displays. It is often suggested as a backup system, but it does represent a fairly high weight and cost investment for a secondary or backup application.

F. NAVIGATIONAL AIDS

1. <u>Introduction</u>

There are several avionic devices which are classified as Navigational Aids (NAVAIDS); and although they do not suffice in themselves to provide an all weather landing capability, they are often used as an essential sensor of an overall system, such as DME in the AILS system, or as the radio altimeter might be used with the present ILS based systems.

2. <u>Distance Measuring Equipment</u>

a. Introduction

Distance Measuring Equipment (DME) operating in the 960 to 1215 MHz range, has been in common usage in all types of aircraft since the early 1950's. The equipments have improved with the advancing component technology; however, the concept has remained basically the same.

In more recent years, other techniques have evolved for the purpose of performing distance measuring including Miss-Distance Indicators (MDI) for missile accuracy evaluation, exotic pseudo noise techniques for space applications, and various other techniques to meet the increasing needs of limited and tactical warfare. In order to make a comparative analysis and establish trends, it is necessary to briefly discuss the principles of operation of each of these techniques.

b. Principles of Operation

(1) DME (Reference 35)

The UHF DME system consists of airborne equipment known as interrogator responders (commonly shortened to interrogator) and ground equipment referred to as transponder or beacon, but more appropriately called transponder. The cycle of events that results in the determination of distance begins with the modulator in the interrogator equipment. In the modulator, pulses are generated having lengths of a few microseconds. The rate at which these pulses are generated is rather low, and seldom exceeds 150 per second. These pulses are usually generated in pairs for coincidence pair detection. The output of the modulator is applied to a radio frequency generator that incorporates provisions for operating on a number of different radio frequency channels. A common antenna is used for transmission and reception at two different frequencies.

The interrogator pulses travel to the ground where they are picked up by the transponder antenna, which has a nondirectional horizontal plane pattern but a directional pattern in the vertical plane. The pulse signals are detected, then used to modulate a new frequency for transmission back to the interrogator.

The signals received from the ground transponder are detected and compared with a signal from the modulator. A search-and-tracking unit determines which of all the signals received have a fixed time delay with respect to the transmitted signals. This is a necessary operation for there may be a number of aircraft with equipments interrogating the same transponder, and it is necessary to determine which of the pulses are replies to the specific interrogator in question. The modulator has been designed to produce pulses having an intentional jitter so that there is little probability that several aircraft can continue to send pulses at exactly the same time. Having determined which of the received pulses are due to its interrogator, the search-and-tracking unit locks onto these and continuously measures relapsed time between transmission and reception to accuracies sometimes within 0.16 kilometer (0.1 mile).

(2) MDI

The Miss-Distance Indicator (MDI) System is also a pulse system similar to the DME system. However, instead of controlling the rate of modulation of the pulses in the interrogator, the interrogator is triggered by a pulse received from the transponder. Of course, the interrogator must transmit at least one pulse in order to start the chain reaction. Thus, each modulator is triggered by a pulse received from the other unit. The rate of triggering or the pulse rate is then inversely proportional to the total delay time between the two units and therefore, inversely proportional to range separation. This is very simple to implement; however, a major disadvantage is that operation is limited to one interrogator and one transponder at a time. Consequently, this technique has found its application in the measurement of range separation between a target and a vehicle where simplicity of operation and high accuracy and resolution are needed, but where multiple operation between units is not required.

(3) CW Ranging Systems

Continuous wave (CW) ranging systems are similar to pulse systems in that they usually consist of an interrogator and a transponder. However, instead of measuring a time difference, a CW system measures a phase difference where the phase may be in an unmodulated carrier or in a modulating frequency usually applied to the carrier as a frequency modulation signal.

The accuracy of CW systems for measuring range is dependent upon the signal-to-noise ratio of the information and the accuracy and stability of the components affecting the calibration. Usually, the signal-to-noise ratio can be kept large, except for space missions. A single unmodulated high frequency carrier exhibits excellent range resolution as defined by carrier phase measurement; however, the ambiguity of the measurement prevents such a simple approach. Two unmodulated carrier frequencies improve the ambiguity by an amount dependent upon their frequency separation. Multiple carriers are used in microwave surveying equipments and are capable of extremely fine resolution where the surveying points are held fixed and ample time is taken for the measurement.

Phase lock techniques are often used to measure range using the phase characteristics of the carrier and its modulation. The pseudo noise technique is an advanced method of obtaining synchronization and resolving ambiguity in a phase lock system and effectively narrows the information bandwidth to obtain communication efficiencies approaching the limits defined by Shannon. The complexity of the technique is usually justified only for systems where extreme range is required, or where security of the ranging signal is of prime importance. Hence, a pseudo noise technique is overly complex for general all weather landing applications.

The simplest modulated CW approach compares the phase of a ranging tone after its return from a remote transponder with the phase of the original ranging tone at that instant of time; the phase difference is a function of range. The use of several coherent ranging tones permits high resolution and accuracy without loss of range unambiguity. This approach is used in the Cubic Corporation's SHIRAN System for geodetic mapping and surveying.

Other techniques have evolved from the FM-CW technique used for radio altimeters. Here, the return signal of a frequency-modulated carrier is mixed with the originally transmitted signal to produce a frequency-modulated output signal whose modulation index or frequency deviation is a function of the range. This signal can then be processed in a number of ways by holding certain parameters fixed and causing other parameters to vary as a function of range. These techniques have resulted in systems which are capable of relatively high accuracy and resolution while remaining relatively simple to implement. However, any CW system is more difficult to implement for multiple aircraft operation than a pulse system if frequency conservation is an important factor. A pulse system has an inherent capability for the time-sharing of the signals from several aircraft, as described in the DME section.

c. Performance, Present and Future

As a technique for measurement of the range from several aircraft to a remote ground location, the UHF DME system is the present standard because of general acceptance. More elaborate versions, such as that described for the AILS, are capable of accuracies of the order of 1 percent. FM-CW systems are capable of comparable accuracy and resolution of the pulse systems with generally less complexity of instrumentation. Furthermore, a CW system is more adaptable to data transmissions; however, a pulse system is more adaptable to sharing the ranging functions with other aircraft. For all weather landing systems, it is probably more important that a multiple aircraft capability exist; therefore, it is probable that pulse techniques will be preferred for distance measuring in general avionics.

Recent advances in the technology of solid-state power generation will probably result in the first major breakthrough in the implementation of DME equipments. Furthermore, it is expected that the frequency of DME operation may, in the future, be increased to a higher band in the spectrum. Thus, it can be concluded that the techniques of distance measurement are many and varied, and it is probable that a technique exists to achieve any desired accuracy or resolution which is practical; it only remains for the component technology to advance in order to simplify the implementation of DME equipments.

3. Radio Altimeters

a. Principles of Operation

The previous section discussed DME equipments; the radio altimeter is a form of DME equipment except that the ground transponder is replaced by a passive reflecting, ground, and isolation between the interrogator's transmitted and received signals is accomplished using two antennas separated from each other. Although some radio altimeters used a pulse time measuring principle, more recent system use FM-CW techniques.

Earliest FM-CW systems used a frequency counting technique to determine the deviation of the mixer output signal which, as explained in the discussion of DME systems, is a function of range. This approach is susceptible to so-called step-error which limits the resolution of the system to the range represented by one cycle of the frequency counted. This step-error can be held to a sufficiently small error if the carrier frequency is deviated by a large amount. This type of system is suceptible to leakage signal paths internal to the equipment, as the leakage path along the skin of the aircraft between the transmitter and receiving antenna apertures or a multiple bounce signal between the aircraft and the ground. The latter is largely a function of the antenna separation, antenna patterns, and the propagation or reflection characteristics of the ground and the bottom surfaces of the aircraft in the vicinity of the radio altimeter apertures.

There are several ways of eliminating or minimizing the effects of these leakage signals. A more sophisticated approach uses the Bessel function characteristic of the side-band energy of the frequency-modulated signal. A simpler approach which has been adopted in more recent radio altimeters purchased by the airlines uses a tracking filter to eliminate interference signals which occur at ranges a few percent removed from the true return signal. Thus, the concept of measuring altitude has been fairly well standardized as to the best basic approach. The differences in the various systems are usually associated with the means of implementation, calibration, and self-test procedures.

b. Performance, Present and Future

The more recent puchase of altimeters by the airlines has been to an ARINC specification of 2 feet or 2 percent. With favorable ground conditions, this accuracy could be halved. However, under poor terrain conditions, this accuracy will be difficult to maintain. Since the radio altimeter reads altitude above the terrain, the accuracy of positioning the aircraft vertically with respect to the runway extension plane will also depend upon the terrain.

G. SUMMARY AND CONCLUSIONS

The present world standard and reference point for landing systems is the Instrument Landing System (ILS). Presently ILS is not truly a landing system in that it can not provide vertical guidance below about 100 feet above the runway. Its primary limitation is its ability to define the aircraft's position with desirable precision for automatic touchdowns because of the influence of terrain and structures on the fixed radiation beam pattern. The use of larger antennas for both localizer and glide slope is improving the accuracy of ILS; however, its operation in UHF spectrum is resulting in antennas which are very large. An example is the FAA's 35.66-meter (117-foot) long slotted waveguide localizer antenna. The primary advantage of continuing to strive for more accuracy of the ILS system, in addition to the world standard status, is the fact that the aircraft's position data is air-derived.

This capability, coupled with a ground radar for monitoring is considered an ideal approach for providing equipment redundancy. Conversely, it can be stated that the primary disadvantage of ground-based radar data link system is the lack of air-derived data. In practice, the radar technology has advanced such that accuracies of the order of -0.03 degree are obtainable even at the low elevation angles involved in aircraft landing.

A more sophisticated approach has been adopted in the Airborne Instrument Laboratory's AILS system which, under FAA sponsorship, adopts the advantage of both ILS and ground-based radar in an integrated system of air-derived and ground-derived data. There can be little argument with the basic philosophy behind this system although it must be determined if the advantages of the system are sufficient to outweigh the increased complexity and cost of the system. There is no fundamental reason why the system cannot achieve its desired angular accuracy of 0.01 degree and 1 percent in range. Whether or not the methods of implementation are the most efficient and accurate is a matter of radar technology.

Although the artificial imaging systems would appear to be the nearest form of visual reproduction for maximum pilot involvement in the landing process, the electromagnetic sensor required in the aircraft is relatively large, and the imaging system is also large and must be located in an already overcrowded pilot's compartment. Thus, the acceptance of this approach must be preceded with considerable technology advancement in airborne microwave monopulse receivers and windscreen display subsystems.

In conclusion, there are two leading system approaches to all weather landing. The preferred, if it can do the job, is improved ILS in conjunction with improved controls and navigational aids as required. If the aviation industry determines that this approach will not consistently and reliably provide all weather landing, then a more sophisticated approach must be undertaken, and here the AILS system must be considered one of the leading contenders.

In the area of navigational aids, the radio altimeter technology appears to be fairly well-advanced due to recent developments by several companies in competition for the commercial aviation market. Distance measuring techniques, however, are undergoing rapid changes and the optimum approaches are not yet definitized. Thus, some further development in this area is to be expected in the next few years. If the requirements for all weather landing can be met with sensors having angular accuracies of 0.01 degree and range measurement accuracies of 1 percent, then the electromagnetic sensor technology is sufficiently advanced and it only remains to improve the implementation in terms of the usual size, weight, cost, and reliability considerations.

If any one area of investigation is to predominate, it is probably the need to consolidate some of the many functions required for total aircraft navigation including on-course navigation, air traffic control, and approach and landing. The objective is not to eliminate already existing equipment from the airplane as much as it is to make greater use of existing equipment or improved versions of existing equipment to perform more functions better, more accurately, and more economically.

SECTION V

REVIEW OF LANDING SYSTEM CONTROL CONFIGURATIONS

This section presents a summary of the control configurations used in present day jet transport automatic landing systems. The theoretical concepts behind these systems have been discussed previously in Section III, Volume I, of this report. At that time, it was noted that all of these state-of-the-art systems use similar control techniques, but differ somewhat in the manner of synthesizing a given signal from various possible sources of raw data.

Figure 5-1 summarizes the phases of the automatic approach and landing. For lateral control they are:

- Localizer Capture
- Localizer On-Course (or track)
- Approach On-Course (fine track)
- Forward Slip Initiation (for those systems using this method of final cross-wind alignment) or decrab initiation
- Runway Steering

The phases of the vertical control are:

- Glidepath capture
- Glidepath On-Course (or track)
- Glidepath Extension
- Flareout

Note that the glidepath extension phase does not necessarily imply a new set of control laws. In general, it corresponds to that part of the vertical flight path between altitudes of about 45.72 meters (150 feet) and 15.24 meters (50 feet) when the glide slope signal gain is programmed downward toward zero. In some systems, the only closed loop control remaining when the glide slope gains reach zero is that of pitch attitude hold. In others, the pitch attitude hold is augmented by a vertical speed loop that attempts to maintain the glide slope rate of descent.

The aircraft for which the automatic landing system summary is compiled are as follows:

- Trident
- BAC-111
- VC-10
- Boeing 707
- Boeing 727
- Boeing 737
- DC-9
- Caravelle

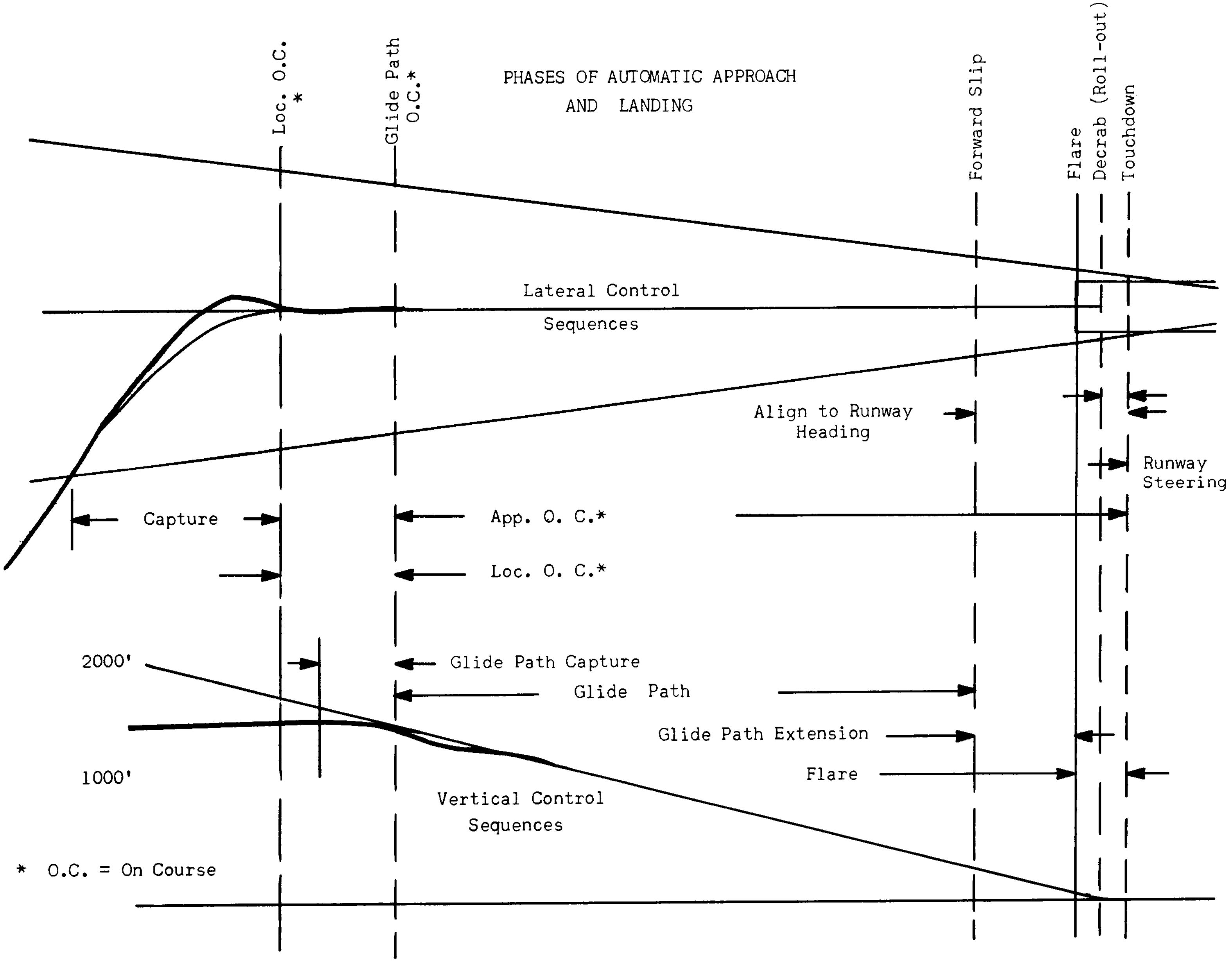


Figure 5-1
Phases of Automatic Approach and Landing

Table 5-1 summarizes the lateral control functions provided in each of these aircraft. These functions are used to generate a roll command. The three British aircraft (Trident, BAC-111, and VC-10) use what is essentially the BLEU system. For lateral control, they do not employ heading data for cross-course damping and never use integral compensators. They use localizer rates for damping and consequently take some penalty in excessive control for poor quality localizer beams. They also include an automatic decrab function that is initiated by a radio altimeter measurement of altitude above the runway.

The Boeing aircraft systems do not include the automatic decrab. Since these landing systems are aimed at Category IIIA operations at this time, the decrab, if desired, can be applied manually since visual contact with the runway will exist for Category IIIA at the decrab altitudes. Also, the Boeing aircraft can tolerate considerable crab angle misalignment at touchdown. The DC-9 system uses the forward slip technique of final approach so that the aircraft heading is aligned with the runway centerline at touchdown. Alignment to the runway heading starts at about the same time that the glide slope extension phase begins; that is, when glide slope gains are programmed downward toward zero.

Table 5-2 summarizes the vertical control functions provided in the eight aircraft listed above. The BLEU systems remove glide slope control between 100 and 200 feet, and maintain attitude hold until flareout. The flareout data for these systems are derived entirely from the radio altimeter. The other systems continue on glide slope control during the extension phase, but the gains are at zero before the flareout altitude is reached. In the DC-9 and Caravelle, vertical speed control augments the pitch hold mode during the very short interval between ineffective and zero glide slope gain and flareout. The Caravelle system is the only one that uses barometric $\dot{h}$ information during flareout.

TABLE 5-1

SUMMARY OF SIGNALS USED FOR LATERAL CONTROL

Aircraft	Equipment Manufacturer	Localizer On-Course				Approach On-Course					Runway Alignment	
		y	$\dot{y}$*	$\int y$	ψ_e**	y	$\dot{y}$	$\int y$	ψ_e	Lag ϕ	Forward Slip	Decrab
Trident	Smiths	X	X			X	X					X
BAC 111	Elliott/Bendix	X	X			X	X					X
VC-10	Elliott/Bendix	X	X			X	X					X
Boeing 707	Bendix	X	X		X①	X	X	X	X①	X		
Boeing 727	Sperry	X	X	X	X	X	X	X	X	X		
Boeing 737	Sperry	X	X	X	X	X	X	X	X①	X		
DC-9	Sperry	X	X	X	X	X	X	X	X		X	
Caravelle	Lear	X	X			X	X			X		X

BLEU SYSTEMS

y = Localizer deviation.

ϕ = Roll angle.

*$\dot{y}$ = Represents lateral velocity obtained by differentiating the localizer beam singal.

**ψ_e = Represents azimuth angle between runway centerline and aircraft.

① = Washed out heading.

TABLE 5-2
SUMMARY OF SIGNALS USED FOR VERTICAL CONTROL

Aircraft	Equipment Manufacturer	Glidepath			Glidepath Extension				Flare		
		Δh	$\int \Delta h$	$\dot{h}$	Δh	$\int \Delta h$	θ	$\dot{h}$	h	$\dot{h}$	$\int (h + \dot{h})$
Trident	Smiths	X	X				X		X	X①	X①
BAC-111	Elliott/Bendix	X	X				X		X	X①	X①
VC-10	Elliott/Bendix	X	X				X		X	X①	X①
Boeing 707	Bendix	X	X		X	X	X			X②	X②
Boeing 727	Sperry	X	X	X③	X	X	X			X②	X②
Boeing 737	Sperry	X	X	X③	X	X	X			X②	X②
DC-9	Sperry	X	X	X④	X	X	X	X④	X	X②	X②
Caravelle	Lear	X	X	X③	X	X	X	X③	X	X③	X③

Δh = Glidepath deviation
$\dot{h}$ = Vertical speed
h = Radio altitude
θ = Pitch angle

<u>NOTES</u>: ① $\dot{h}$ derived from radio altitude.
② $\dot{h}$ signal from radio altitude and normal acceleration.
③ $\dot{h}$ signal obtained from barometric altitude and normal acceleration.
④ $\dot{h}$ signal obtained from barometric altitude.

SECTION VI

DISCUSSION OF REDUNDANCY AND MONITORING TECHNIQUES

A. INTRODUCTION

The information contained in this section provides a brief review of redundancy concepts being implemented or under consideration for all weather landing systems. Although the disadvantages and advantages of various approaches are noted, it is not possible to make a judgment regarding superiority of any particular approach without considering the complete context of the specific application. In general, then, one would expect to find many different configurations in the state of the art, all aimed at approaching the idealized objectives of a fail-operational capability. It will be observed that the configurations discussed are those of analog control systems which are used exclusively in the present state of the art of all weather landing systems. All data that is processed, computed, transmitted, and measured is in analog format. Digital system state of the art has not reached the same level of development as it has for the analog systems. While integrated digital avionics are being developed with redundant computer configurations, such systems have not been required to achieve fail-operational capability where no failure in sensors, switches, power supplies, computers, indicators, data processors, etc, can be allowed to occur so that normal system operation is disrupted even momentarily.

Included in this review of redundancy concepts is a glossary of terminology. Also included is a discussion of the automatic landing considerations that determine the level of redundancy required. Typical calculated probability of failure for a representative type of triplex system is included.

B. DEFINITION OF TERMINOLOGY

1. <u>Indirect Monitoring</u>

This term is used to describe a monitoring technique whereby a functional element or system's performance is assessed by measuring one or more parameters, based on a prior knowledge of the behavior of these parameters either as discretes or as a function of time. A level detector of a power supply output or a wheel speed detector in a rate gyro are simple examples of the indirect monitoring techniques. A more subtle example might be a measurement of the time that a servo is hardover. Based on a knowledge of system operation, it is sometimes possible to choose a hardover time, which if exceeded is an indication of failure.

2. Model Monitoring

Model monitoring, as the term implies, involves the assessment of a functional element or system's performance by direct comparison of the output with a model of the element or system, both receiving the same inputs. If the model is implemented as a complete second operating channel, one of the systems can act to oppose the other when an active failure occurs.

3. Comparator

Any device which is used to compare two signals and will change state based upon absolute or time functions of the differences between the two signals.

4. Comparison Monitoring

Performance assessment based upon direct comparison of two signals.

5. Crossfeeding

A technique commonly employed in redundant systems containing more than one redundant section. Signal outputs of one redundant section are crossfed to a downstream redundant section, such that all downstream channels receive identical total inputs irrespective of the relative state of the incoming signals.

6. Majority Vote Logic

A decision circuit which identifies a faulty element or channel in a triplex system based upon a two-out-of-three vote.

7. Mid-Value Logic Circuit (MVL)

A signal circuit containing AND-OR logic elements. With three input signals, the circuit passes the input signal which is the mid-value of the three input signals. For example, if the three input signals are 1, 2, and 5 volts respectively, the output voltage will be 2 volts. (This is also referred to as an Intermediate Signal Selector Circuit.)

8. High Gain, Low Saturation, Fail-Operational Technique

A redundant circuit or system which depends upon a high, open loop gain and a low saturation characteristic whereby the output remains essentially unchanged in the presence of single failures independent of failure detection.

C. ALL WEATHER LANDING CONSIDERATIONS

Because the automatic landing phase of flight is the most critical from a safety standpoint and occurs at the end of a flight, it sets the most stringent requirements for the reliability, redundancy, monitoring and failure reporting portions of an AFCS. In this section, the all weather landing requirements are discussed. The FAA Low Minimums Categories referenced in the discussion are summarized in table 6-1.

TABLE 6-1

FAA LOW MINIMUMS CATEGORIES

Category	Decision Altitude	Horizontal Visibility-Meters (Along Runway)
I	200	796.48 (2600 feet)
II	100	365.76 (1200 feet)
IIIA	0	213.36 (700 feet)
IIIB	0	45.72 (150 feet)
IIIC	0	0 (0 feet)

The FAA has not defined either the performance or the safety requirements for aircraft operation under Category III weather minimum conditions. For Category II and IIIA certification tests, however, the FAA has assumed that any type of AFCS failure can occur during the landing phase, and has required that the failure occurrence be detected and indicated, and that a subsequent safe alternate course of action be available. For Category II and Category IIIA operation the alternate is generally a safe go-around. As weather minima are reduced, a go-around will be a less desirable alternate, and more emphasis will be placed on the accomplishment of the landing in the presence of automatic equipment failures.

It is expected that Category IIIB and IIIC operations will require the existence of a fail-operational automatic landing system at the start of the critical landing phase (possibly, at 100 feet) in order for a Category IIIB or IIIC landing to be continued past that point. This will require that occurrence of any failure which affects a system's fail-operational status be indicated to the pilot to allow him to decide whether to continue past the 100-foot point or to go around.

For any Category IIIC system, the airlines will desire reduced capability operation under Category IIIB, A, and Category II conditions, depending on the availability of specific equipment at specific times during the final approach. This will require failure detection, failure advisement, and manual and/or automatic switching of equipment to achieve safe operation to the lowest possible legal altitudes. In addition, separate go-around guidance for manual control will probably be required. Based on experience obtained during recent Category II and IIIA type certification programs, it is felt that the most probable operational procedures which will be followed for landing under low weather minimums will conform to those outlined in table 6-2.

TABLE 6-

ALL WEATHER LANDING OPER

System Status	Anticipated Legal Operational Approach Capability	Type of System Protection	Anticipated Minimum Operational IFR Altitude	Automatic System Capability After First Failure	Automatic System Capability After Second Failure	First	
						Above 200 Feet	200 to 100 Feet
Three Channels and All Monitors Functioning	Category IIIC	Fail-Operational	Touchdown	Category IIIA (dual channel)	Category II (single channel)	1. Auto disengage failed channel. 2. Continue with dual channels to 50 feet <u>or</u> go-around manually if field is below Category IIIA minimums. 3. Subsequent approaches may be made to 50 feet under Category IIIA minimums.	1. Auto disengage failed channel. 2. Continue with dual channels to 50 feet <u>or</u> go-around manually if field is below Category IIIA minimums. 3. Subsequent approaches may be made to 50 feet under Category IIIA minimums.
Two Channels and Associated Monitors Functioning	Category IIIA	Fail-Safe	50 feet	Category II	None	1. Auto disengage both channels (complete axis). 2. Go-around or continue to 100 feet with manually selected single channel. 3. Subsequent approach with single channel can be made to 100 feet under Category II minimums.	1. Auto disengage both channels (complete axis). 2. Go-around manually. 3. Subsequent approach with single channel can be made to 100 feet under Category II minimums.
Single Channel (No Monitors)	Category II	Servo Authority Limits (Plus in-line monitoring of servo portion of system)	100 feet	None	None	1. Pilot disengages and effects manual go-around <u>or</u> continues manually to 200 feet on raw ILS data. 2. Subsequent manual approach on raw ILS data can be made to 200 feet.	1. Pilot disengages and effects manual go-around. 2. Subsequent manual approach on raw ILS data can be made to 200 feet.

TIONAL PROCEDURES

ACTION REQUIRED WHEN FAILURES OCCUR					
Failure		Second Failure			
100 to 50 Feet	Below 50 Feet	Above 200 Feet	200 to 100 Feet	100 to 50 Feet	Below 50 Feet
1. Auto disengage failed channel. 2. Continue with dual channels to 50 feet <u>or</u> go-around manually if field is below Category IIIA minimums. 3. Subsequent approaches may be made to 50 feet under Category IIIA minimums.	1. Auto land on Dual System with no pilot action required.	1. Auto disengage complete axis. 2. Go-around manually or continue to 100 feet on manually selected single channel of AFCS. 3. Subsequent approaches may be made with manually selected single channel to 100 feet under Category II minimums.	1. Auto disengage complete axis. 2. Go-around manually. 3. Subsequent approaches may be made with manually selected single channel to 100 feet under Category II minimums.	1. Auto disengage complete axis. 2. Go-around manually. 3. Subsequent approaches may be made with manually selected single channel to Category II minimums.	1. Auto disengage complete axis. 2. Pilot attempts to make landing manually with adequate display.
1. Auto disengage both channels (complete axis). 2. Go-around manually. 3. Subsequent approach with single channel can be made to 100 feet under Category II minimums.	1. Not legal to be automatically controlled at this altitude with dual system under Category IIIA minimums.	1. Pilot disengages and continues manually on raw ILS data to 200 feet <u>or</u> effects a manual go-around.	1. Pilot disengages and effects a manual go-around.	1. Not legal to be automatically controlled at this altitude after first failure in Category IIIA minimums.	1. Not legal to be automatically controlled at this altitude after first failure in Category IIIA minimums.
1. Not legal to be automatically controlled at this altitude in Category II minimums.	1. Not legal to be automatically controlled at this altitude in Category II minimums.	DOES NOT APPLY BECAUSE ONLY ONE OPERABLE CHANNEL INITIALLY EXISTED.			

An uncertainty at this time is the degree of attitude and/or path deviation which will be allowed for the first and second failures in a fail-operational system during the critical landing phase. It is anticipated that rather restrictive limitations will be imposed by FAA on effects of first failures. Ideally, second failures should be fail-safe, with perhaps a less restrictive limit on allowable transients. These failure characteristics can be assured to an adequate level of confidence with triplex monitored systems in which devices such as Mid-Value Logic (MVL) circuits are used to effectively block failures in the sensing and computing section of the automatic controls.

D. COMPARISON OF TRIPLEX REDUNDANCY AND MONITORING TECHNIQUES

Four types of triplex monitored systems, usually considered for fail-operational automatic control requirements, are described in this section. They are as follows:

- Summed composite signal transmission
- Mid-value logic signal transmission
- Triplex switched single output
- High gain, low saturation system

For all these systems, tolerance effects are minimized and failures in a particular stage do not actuate failure detection circuits in the downstream stages because the three (or two) channels of the next stage each receive an identical signal from the preceding stage. The difference between the systems relate primarily to the extent of transmission of first and second failure signals before corrective action is initiated by the failure detection circuits, and to the normal transmission characteristics for low-level signals. A subsequent discussion will consider some of the practical steps which must be taken to keep triplex channels tracking when realistic sensor and computer tolerances are considered.

1. Summed Composite Signal Transmission

A block diagram of a typical summed composite signal monitoring stage is shown in figure 6-1. In this type of system, the outputs to each of the channels of the next computing stage are identical and consist of the sum of three signals of the preceding stage. The actual summation is generally made at the input amplifiers of the following stage. The comparators (A, B, or C) act through their associated decision logic circuits to turn off the faulty input signal (at switches 1, 2, 3) and raise the gain (gain 1, 2, 3) of the remaining channels to achieve fail-operational performance at normal gain after first failure. During the time required for actuation of the comparators and the

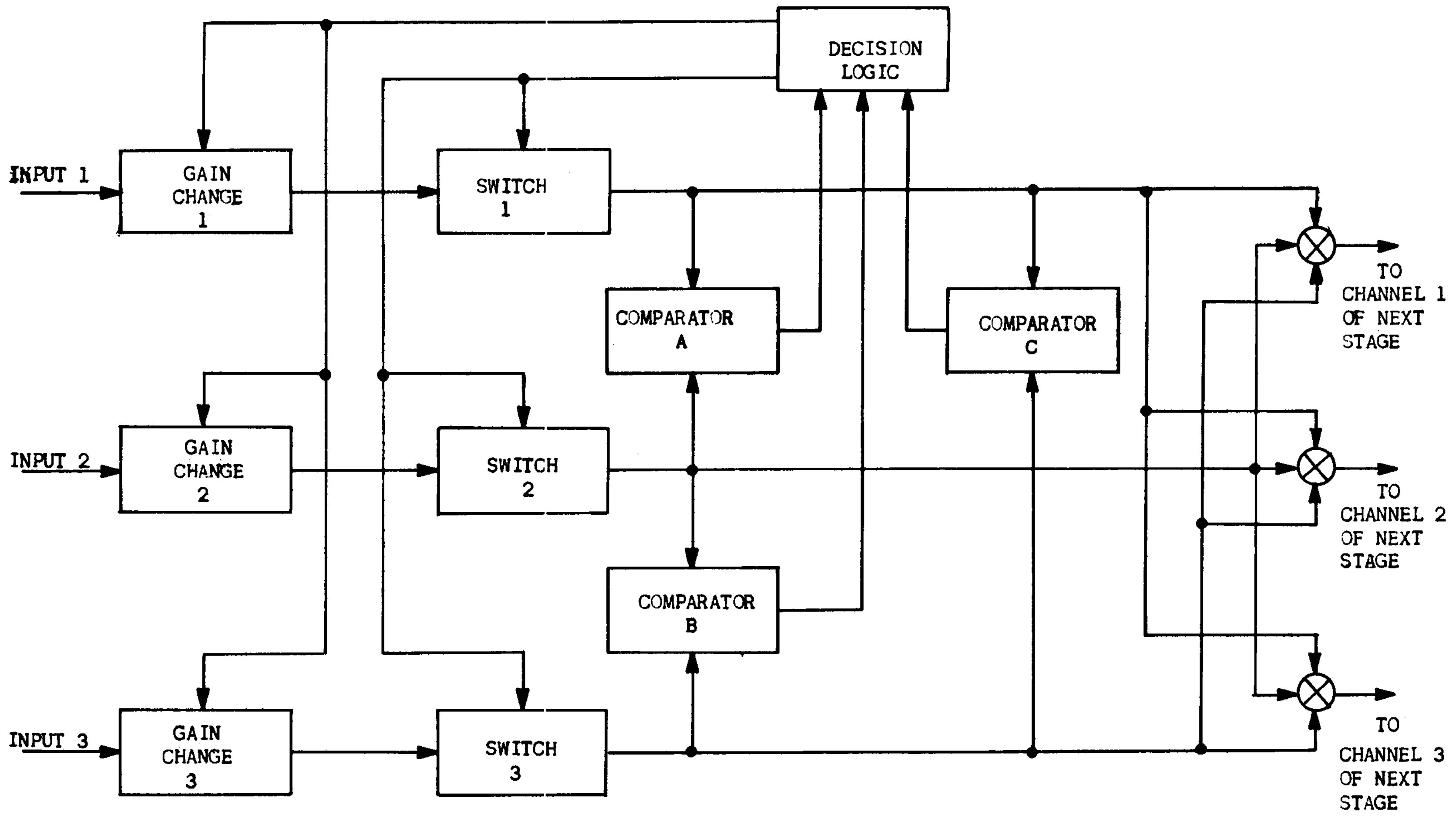


Figure 6-1
Summed Composite Signal Monitoring Stage

switching out of the faulty signal, this signal could result in a transient being applied to the control surface. The severity of the transient would be proportional to the magnitudes of the comparator threshold and its filter time constant, which would normally be selected to be as high as possible in order to minimize nuisance tripping. Further, if a latent failure exists in one of the comparators, a single subsequent hard-over failure could be passed without being detected and removed. Thus, redundant comparators with preflight test, or single comparators with in-flight, "before use" test, would most likely be required for safety. These limitations are primarily responsible for serious consideration of other mixing or voting techniques such as the Mid-Value Logic (MVL) scheme as a more desirable means of meeting the restrictive first-failure requirements of automatic landing systems.

2. Mid-Value Logic System

In the Mid-Value Logic System shown in figure 6-2, the middle value input signal is selected in the MVL signal processing circuits and transmitted to the next stage. If a failure occurs, automatic selection of any new mid-value signal is instantaneously made in the MVL signal processing circuits. Subsequent switchout of the faulty signal is effected by the comparators, decision logic, and switches with no requirement for gain changing. Thus, any failure is blocked immediately without comparator or switch action. Because hard-over protection is not required of the comparators, their threshold and filter-time constants can be set at higher values consistent with better nuisance tripping prevention.

This instantaneous blocking of first hard-over failures will also occur in a dual channel system in which one of the three MVL inputs is normally set at zero. Subsequent comparator action will disengage the channel. The result is a fail-safe MVL system which can logically grow into a full fail-operational triplex MVL system. This hard-over "squelching" will also be effective for second failures of a fail-operational system.

In the MVL system, an undetected latent comparator failure can be followed by any single hardover without transmission of the hard-over to the control surface. In this case, a second hard-over in the same direction as the first would be required before the surface would be deflected. The probability of these three failures occurring in the sequence indicated during a typical 3-hour flight is typically 8.0×10^{-15}. This is sufficiently remote to preclude the necessity of duplicating comparators or of requiring in-flight pretest of the comparators. This advantage results in a system implementation which is simpler than that of the redundant comparator, pretest, signal summing system.

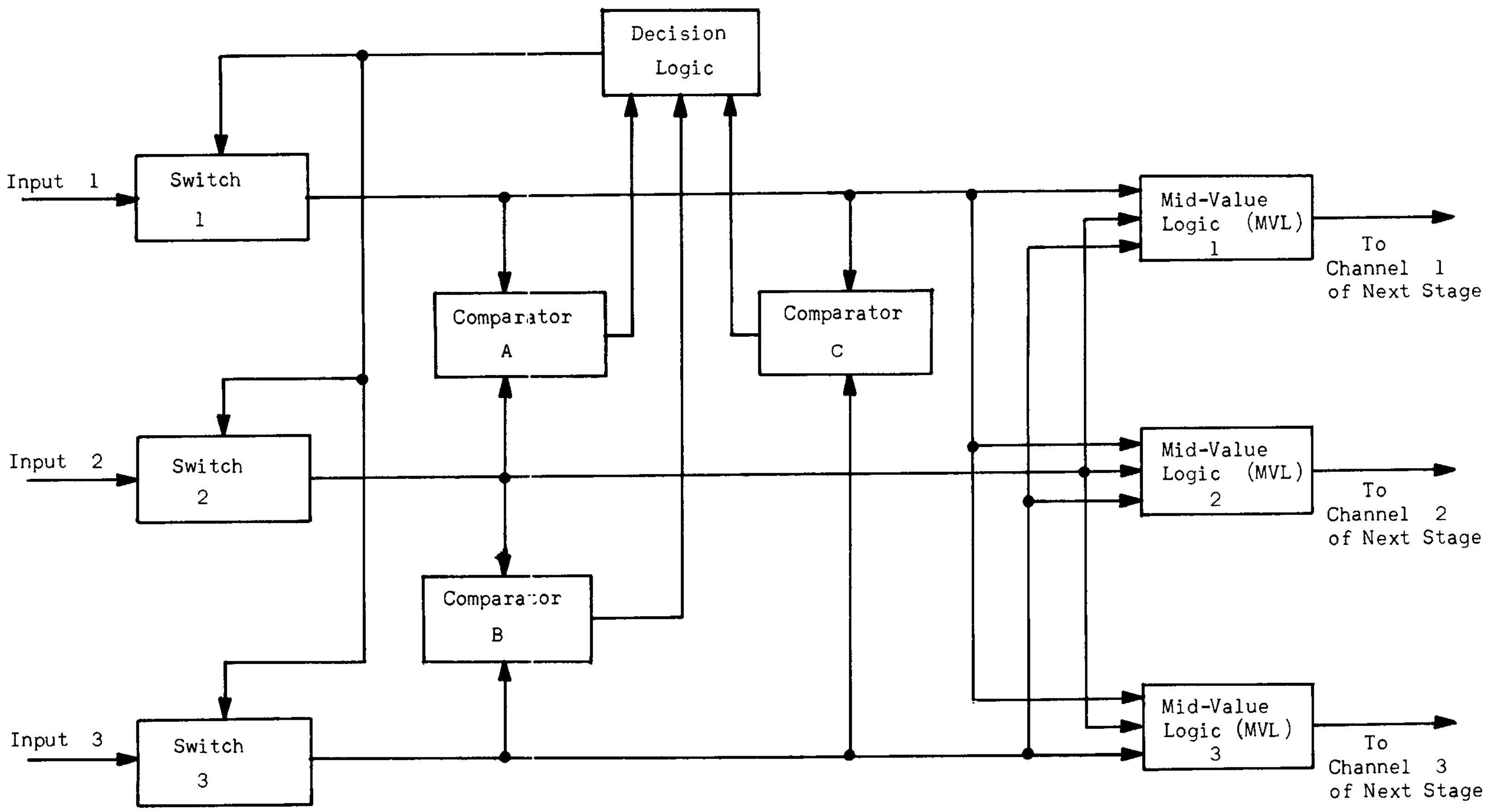


Figure 6-2
Mid-Value Logic Signal Monitoring Stage

It is noted, moreover, that advances in comparator circuit techniques have produced a class of devices known as fail-safe comparators. They are fail-safe in that the failure of any of their components (resistors, capacitors, semiconducter junctions) or failure of their power sources will always indicate a failed state. That is, latent comparator failures can not occur.

3. Triplex Switched Single Output System

Figure 6-3 is a block diagram of a typical triplex switched single output redundant stage. This redundancy and monitoring approach is very similar in operation to the summed composite signal transmission system discussed previously. The triplex switched system of figure 6-3 has only one active channel during normal operation. Input 1 provides outputs to all three channels of the next redundant stage. Inputs 2 and 3 are used only for monitoring purposes. If Input 1 fails, the comparators and decision logic remove the failed channel and switch Input 2 into active use. Input 2 now supplies valid data to all three channels of the next stage. A second input failure disengages the entire system. During single channel operation, any one of the three inputs can be selected for active data transmission.

The only advantages of the triplex switched single output system are as follows:

- No input summing or MVL selection is required. Therefore, cross-channel interaction or failure isolation requirements are minimized.
- There is no requirement for gain changing the input signals as a function of triplex, dual, and single channel operation.

The same disadvantages of comparator detection levels and filter time lags affecting system transients exist for the system as the summed composite signal system. An additional disadvantage of the triplex switched single output system is that the active channel has full authority; and when it fails, the subsequent transient effects are more severe than the summed signal configuration. In the triplex-summed configuration, an input failure has only one-third of the total authority; and furthermore, the two remaining active channels oppose the failure in applications involving rate or attitude feedback.

4. High Gain, Low Saturation System

The high gain, low saturation system uses operational amplifiers connected to a common load to provide instantaneous failure rejection. Figure 6-4 illustrates the amplifier technique. Since the outputs of three high gain devices are connected to a common load with individual feedbacks from load to inputs, a failure of one amplifier or a faulty input to one of the amplifiers is cancelled by the remaining two amplifiers with negligible change in output voltage.

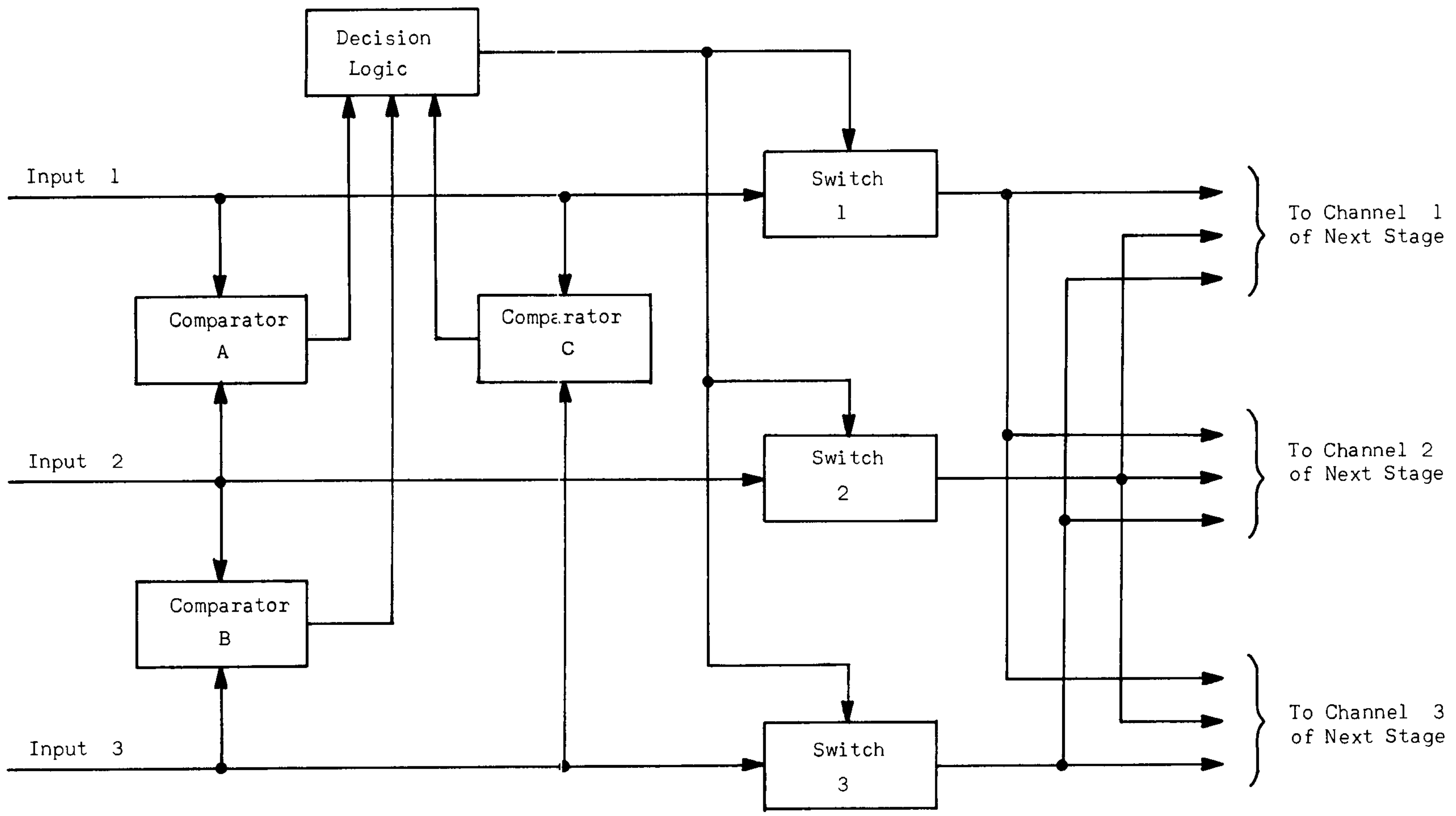


Figure 6-3
Triplex Switched Single Output Monitoring Stage

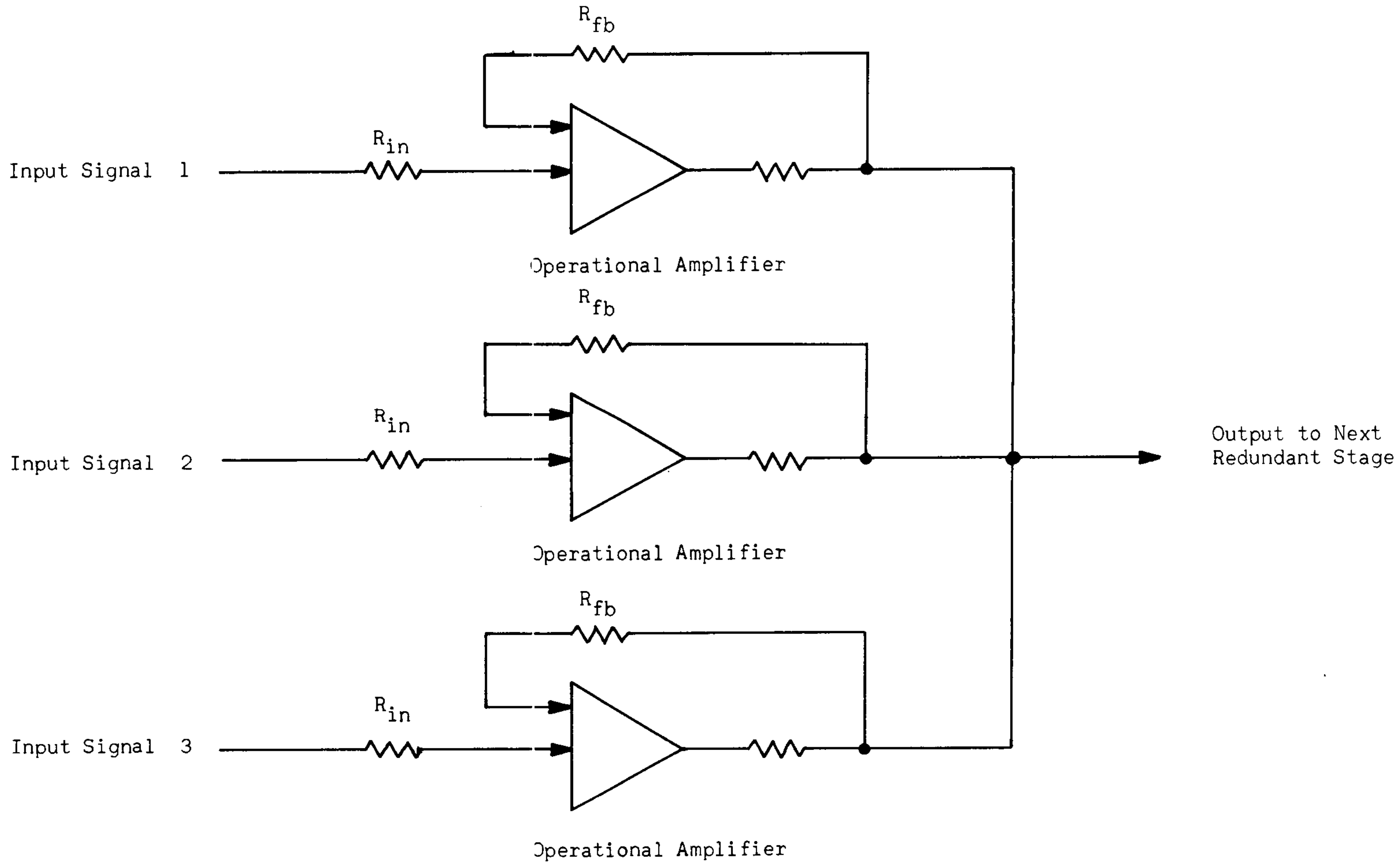


Figure 6-4
High Gain, Low Saturation Summary Technique
(Monitoring Not Shown)

This technique has also been applied to a triplex hydraulic acutator system, where three actuators are force summed into a common load.

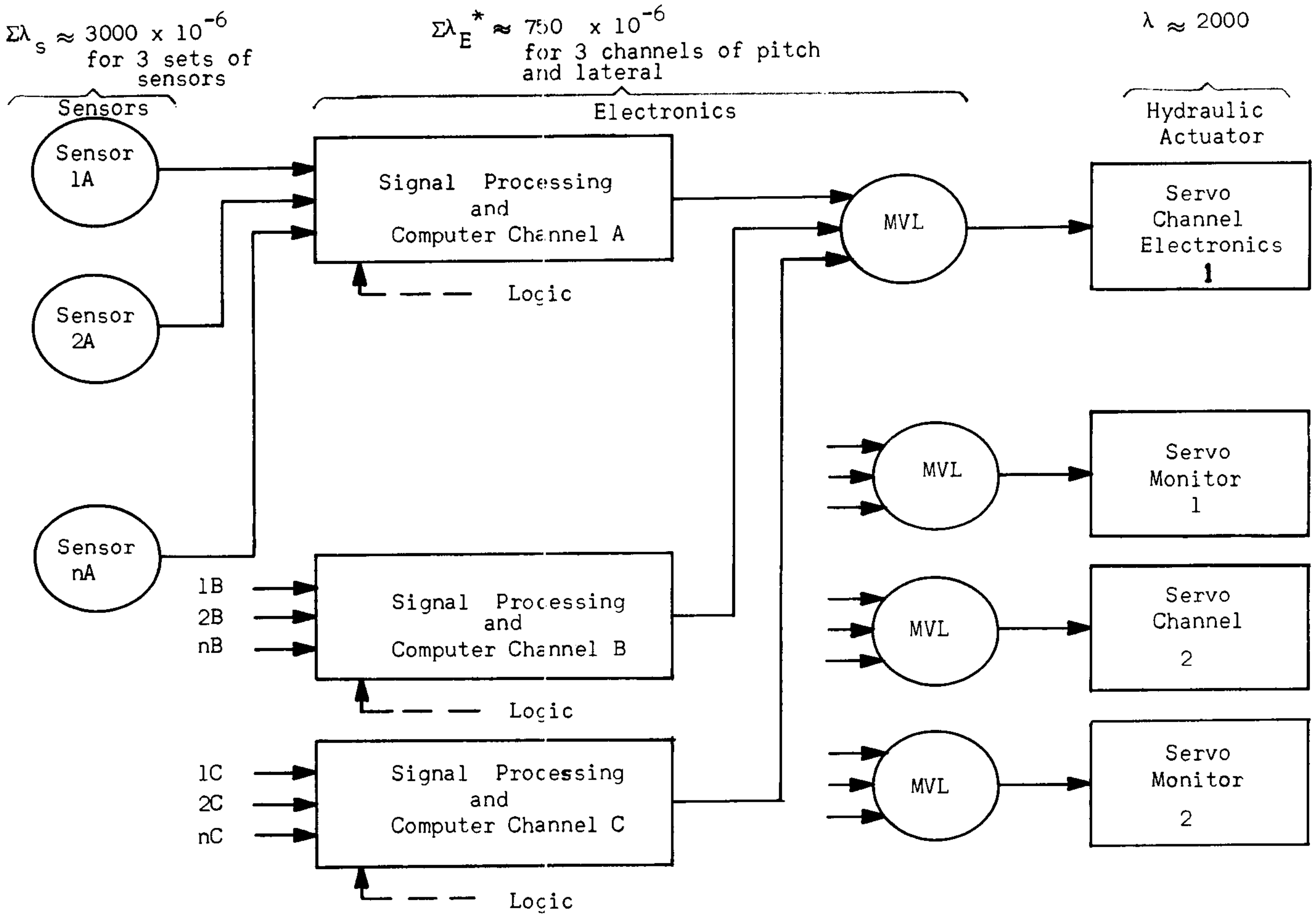
When the high gain, low saturation technique is used in a fail-operational system, either the triplex inputs or the amplifier currents must be monitored to remove the first failure and provide fail-safe performance for second failures.

Although the high gain, low saturation configuration provides instantaneous failure rejection for first failures, the total complexity of the system is usually greater than the Mid-Value Logic System described previously. Also, this configuration has some difficult saturation level and authority problems that compromise overall performance. One advantage over the MVL configurations relates to failure characteristics. An MVL failure appears as an erroneous input to the receiving circuit. Thus, if an MVL feeding a servo amplifier fails, its failure must be viewed as a servo amplifier failure since downstream servo system monitors will be used to detect this failure. In effect, the servo amplifier reliability is reduced by the MVL. However, an amplifier failure in figure 6-4 will not propagate downstream.

E. TYPICAL TRIPLEX (MVL) AWL SYSTEM RELIABILITY

Even though calculated probabilities of failure have not been significantly considered by the FAA in recent Category II and IIIA certification programs, it is very probable that these predictions will be a necessary adjunct of any Category IIIB and C certifications where fully automatic control must be relied on for fail-operational performance. The results of typical calculated probability of failure for a triplex (MVL) AWL system are summarized below to show that the system can meet anticipated safety objectives without the need for in-flight testing of either the control equipment or monitoring and logic circuits.

A simplified diagram of a representative channel is shown in figure 6-5. It includes triplicated sensors and computing channels operating into dual servo electronics and actuators with in-line monitoring of the servo electronics. The monitor and mid-value logic configuration is as described in figure 6-2. System reliability calculations are based on the use of representative average values for the probability of failure of the various elements shown in figure 6-5. A total of three axes (pitch, roll, and yaw) and ten types (sets) of triplicated sensors are conservatively assumed to be required for automatic landing. Conservative state-of-the-art hazard rates are used for the electronic computation, signal processing, servo control, logic, failure monitors, failure reporting logic, and the applicable sections of the mode controller. Less conservative assumptions are used for the sensors which include ILS receivers,



* Includes Processing and Computing, Servo Monitoring, Control Logic, Mode Controller, and Failure Reporting Electronics.

Probability of First Failure for a 30 second flareout interval $\Big\} = \Sigma\lambda t \approx (5750)\ (.0167 \text{ hrs}) \times 10^{-6}$

$= 96 \times 10^{-6}$

Probability of Two Sequential Failures during the 30 second period

$= 9.2 \times 10^{-9}$

Figure 6-5
Reliability Diagram for a Typical Triplex Flareout System

radio altimeters, and inertial measurement devices. These are summarized in the following table:

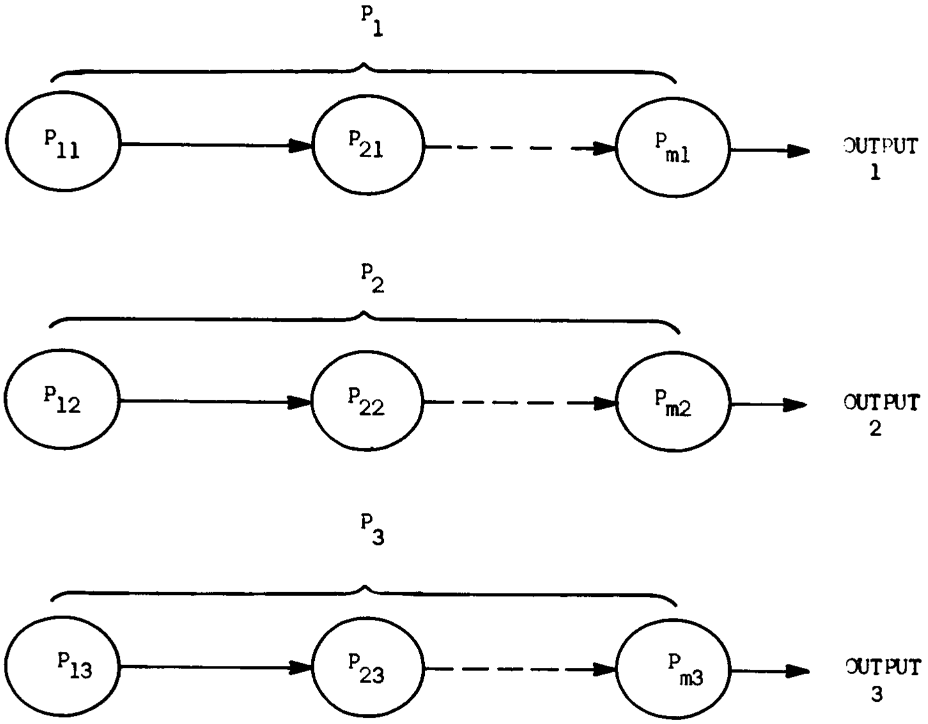
Item	Hazard Rate (any failure) in per 10^6 Hours
Total of Ten Sensors (one set)	1000
Total Sensors (three sets)	3000
All Electronics (includes three channels front end and two servo control channels)	750
Hydraulic Servos (dual) - Pitch, Roll, and Yaw Damper	2000

Based on these hazards, the total probability of any two unrelated failures occurring during the critical landing phase, taken to be 30 seconds, is approximately 9×10^{-9}. This is considerably greater than the usually stated objective of 1.0 failure per 10^7 landings. Moreover, this analysis assumes that a second failure will always cause loss of the control function. In some configurations, less than 10 percent of the second failures will cause a system shutdown. Hence, the probability of a complete loss of function is nearer to 9×10^{-10}.

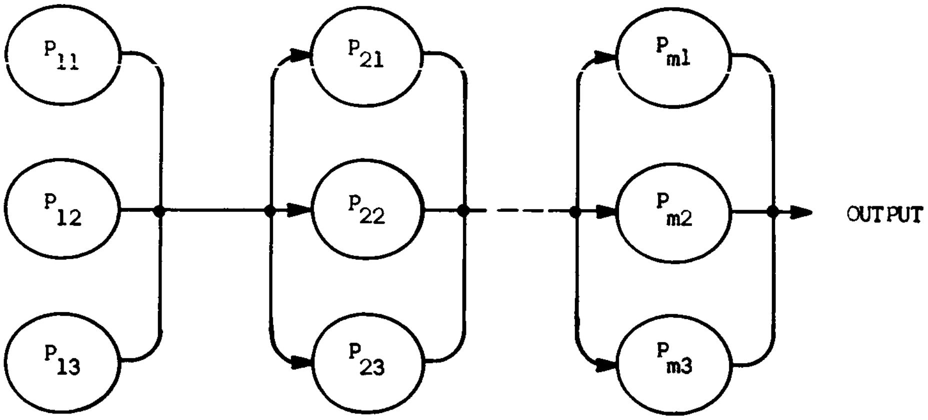
F. REDUNDANCY AND COMPLEXITY

The redundant channel structures, shown in figures 6-1 through 6-4, are conceptual and do not reflect the true complexity of multiple channel automatic control systems. For example, these figures show the interfacing of triplex signals with the signal selection and comparator structure. They do not show how the multiplicity of sensors and computing channels interact. It is in this area that systems can grow to extreme levels of complexity if requirements are imposed naively. For example, consider the problem of group redundancy. This is the term often used to describe a redundancy structure that allows a given system element, such as in individual sensor, to interface with all of the downstream redundant channels. That is, Sensor A will connect to computer Channels A, B, and C. Likewise, Sensors B and C will also connect to all three computer channels. From the reliability standpoint, this arrangement is shown in figure 6-6(b). This figure illustrates how the reliability, R, of a redundant complex, is improved when we allow all of the individual elements having failure probabilities P_{ij} to have the maximum number of paths. The alternate approach, shown in figure 6-6(a) and referred to here as "simple redundancy", keeps the elements channelized and does not allow the transmission of information between channels.

For $P_1 = P_2 = P_3 = P_j$ $R = 1 - (1 - P)^3$



(a) Simple Redundancy



(b) Group Redundancy

$$R = \prod_{j=1}^{m} [\, 1 - \prod_{i=1}^{3} (1-P_{ij}) \,]$$

Figure 6-6
Basic Reliability Redundancy Structure

Group redundancy permits the achievement of a higher level of reliability than simple redundancy for the same number of elements. However, this is a theoretical conclusion that has practically no relevance to the real world. Equipment does not interconnect as nicely as the P_{ij}'s of figure 6-6. Actually, a practical guideline for redundant system design is to minimize the number of interconnecting nodes. This is in contradiction to the theoretical reliability advantage predicted by the maximization of the number of nodes. This principle can be illustrated by showing, in a simplified manner, how the interconnection of elements can be accomplished for a fail-operation AWL flareout system. In this case, let us assume that a radio altimeter, a pitch attitude reference (gyro), a pitch rate gyro, and a normal accelerometer comprise the input sensor requirements. Also, the control and computation channels are triplex, but the servo actuator channel is dual monitored with one electronic servo model used in the monitoring scheme. If each sensor is allowed to transmit to each channel, we have the group redundancy configuration in the front end. A node, however, can not be formed by connecting wires. It takes a device such as an MVL or a summing configuration of the types shown in figure 6-4 to produce one output for three inputs. Thus, figure 6-7 shows how these four input sensors will transmit information to the three computers if MVL's are used. To combine data from triplex groups of four sensors each to three computer channels, 12 MVL circuits are needed.

The complexity problems associated with group redundancy are even more severe than implied by figure 6-7. For example, there are many other secondary communciations pathways that must be considered. For example, logic commands from mode controllers, monitors, programmers, etc, must also transmit information to these computing channels. What type of redundant pattern is to be used for these information pathways? Fortunately, the needed reliability improvements and system performance characteristics can be obtained by simpler redundant structures. It should be emphasized that a major purpose of redundancy is to provide desirable failure characteristics as well as possible reliability improvements. For example, a reason for using an MVL structure is to block propagation of failure transients. It also helps solve problems associated with tolerance build-ups. Figure 6-8 shows the simpler, channelized implementation of triplex flareout control channels. The only possible advantage the group redundancy of figure 6-7 could have provided over this simpler approach is that all three computers would see the same information so that tolerance problems are minimized. However, neither figures 6-7 or 6-8 represent adequate solutions to the problem of tolerance build-up in complex systems. This problem can be solved only by introducing channel equalizations.

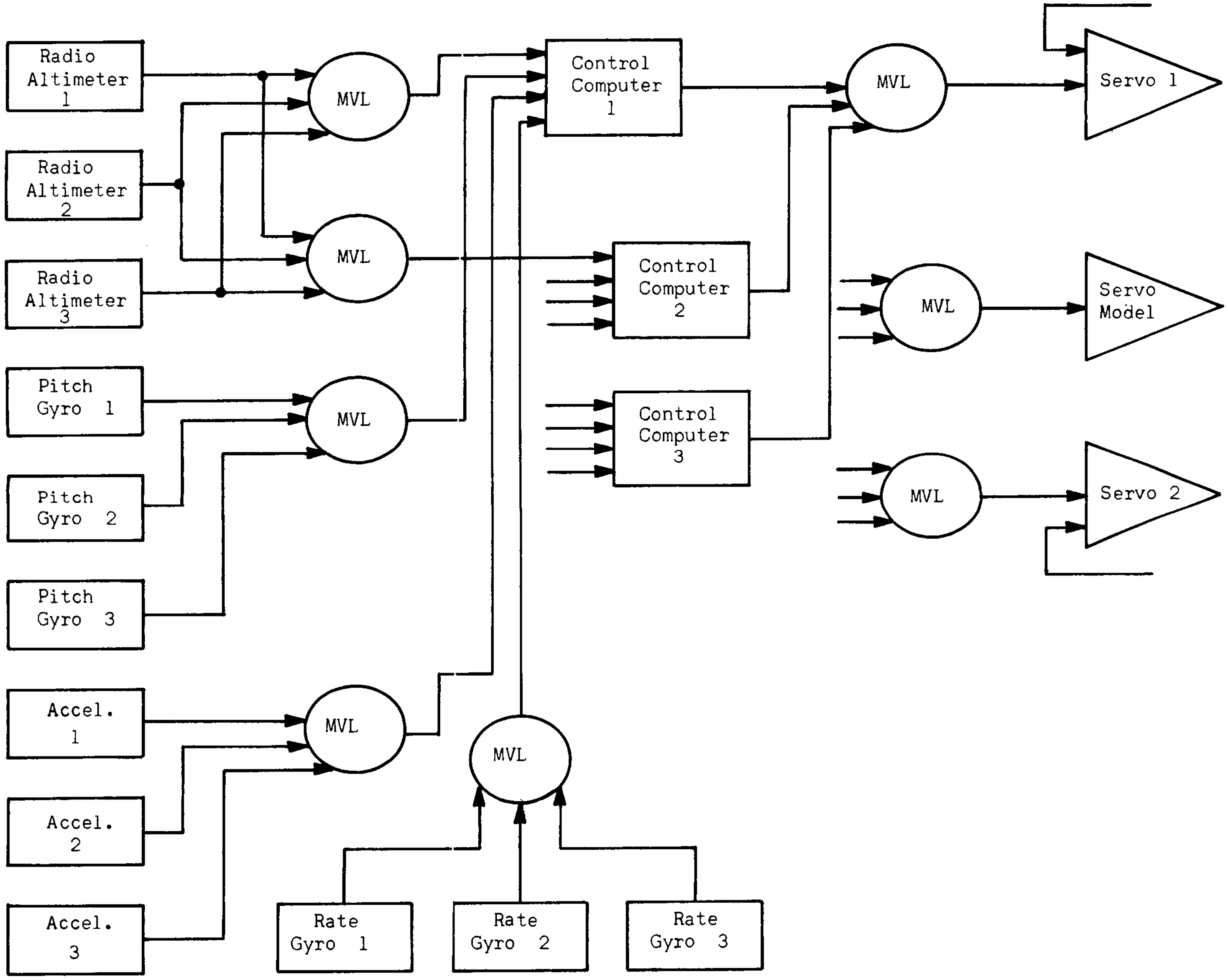


Figure 6-7
Group Redundancy with Separate Voting of Sensors and Computers

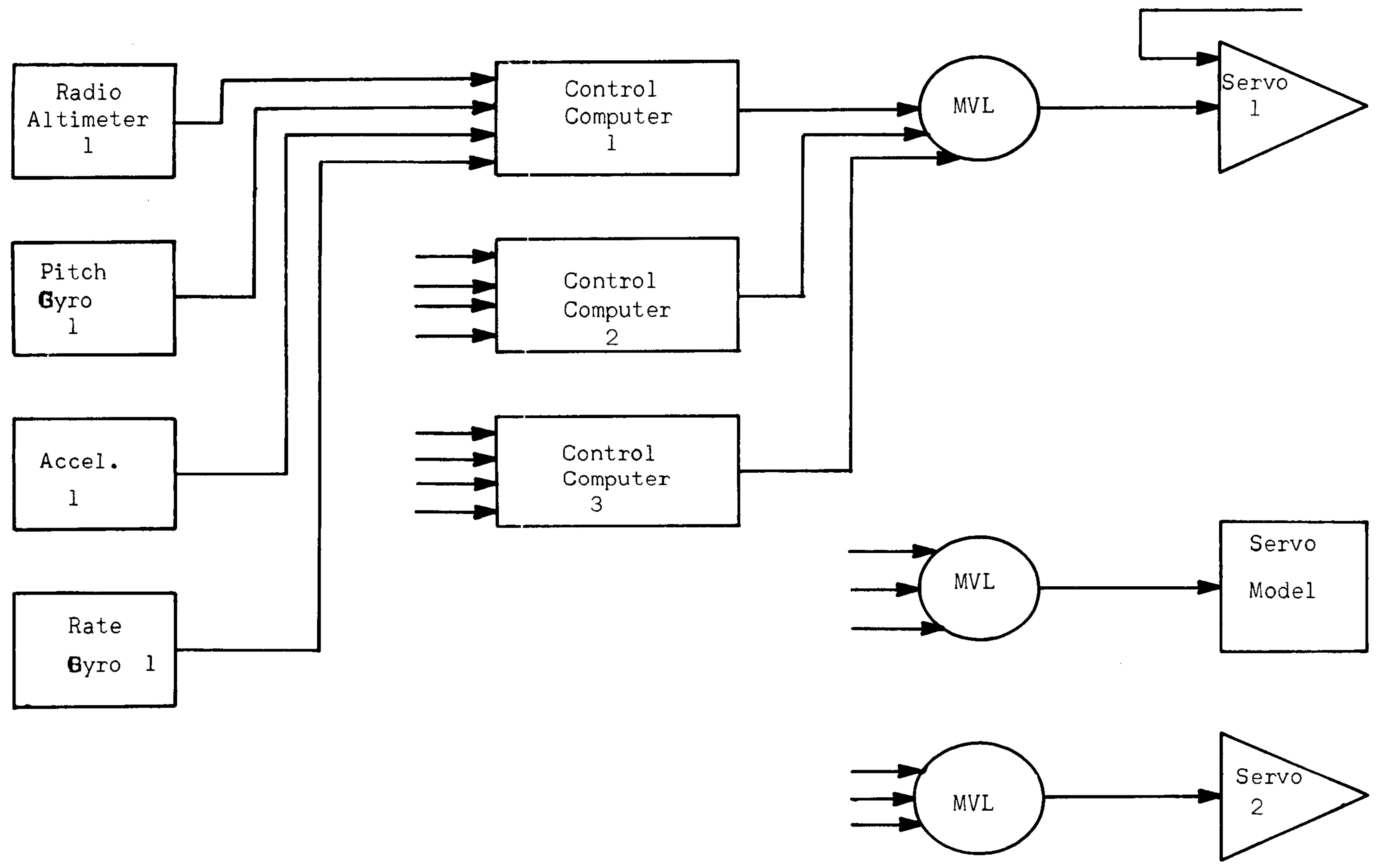


Figure 6-8
Triplex Redundancy with Channelized Computers and Sensors

The redundant configurations discussed thus far assume that the information and control signals transmitted through each of the three channels track each other within reasonable tolerances. Control laws that include low frequency compensators and especially integrators can lead to situations where accurate channel tracking is not possible without cross-channel feedback. In the case of integrators, there is a tendency to drift to a hard-over state unless proper balancing signals are applied. In typical control configurations, these balancing signals are obtained by a closed loop process. In effect, the integrators are constrained by signals developed through various feedback loops. In a single channel system, a stable equilibrium condition is produced by a small feedback signal that acts to balance all nulls and drifts of a channel. In a multiple channel system, each channel has a unique balance condition, but there is only one aircraft to move and thereby create the necessary feedback. A typical phenomenon with three channels containing integrators is an output null that is maintained while the individual channels diverge toward hard-over conditions. The diverging channels maintain the algebraic null until they saturate and then the system breaks down. The usual way to avoid this difficulty is to use cross-channel equalization. That is, all the channels are forced to track at low frequencies. In effect, the three channels are slaved to each other in the steady state.

Figure 6-9 illustrates one method of accomplishing cross-channel equalization. Here, the Channel ① output is compared with the mid-value of the Channel ①, ② , and ③ outputs and the difference is applied to an integrator that forces Channel ① toward this mid-value. The slaving reference could also have been the algebraic average of all three channels. In practice, the slaving integrator is actually the integrator that is included within the control law so that it is inside rather than outside the channel computer.

It is immediately apparent that cross-channel equalization can create as well as solve problems. First, it introduces an interconnection between channels; but safety and reliability rules require that failures within one channel be isolated from the other channels. Equalization permits failure propagation across channels but at a slow rate. A specific design problem is to determine the best compromise between isolation and equalization time. Other problems involve the stability of the equalization loops. It is also possible to effectively change the control laws through the equalization loops and thereby affect aircraft-autopilot dynamic performance. The specific equalization techniques used in a given application usually depend upon factors that are unique to that application.

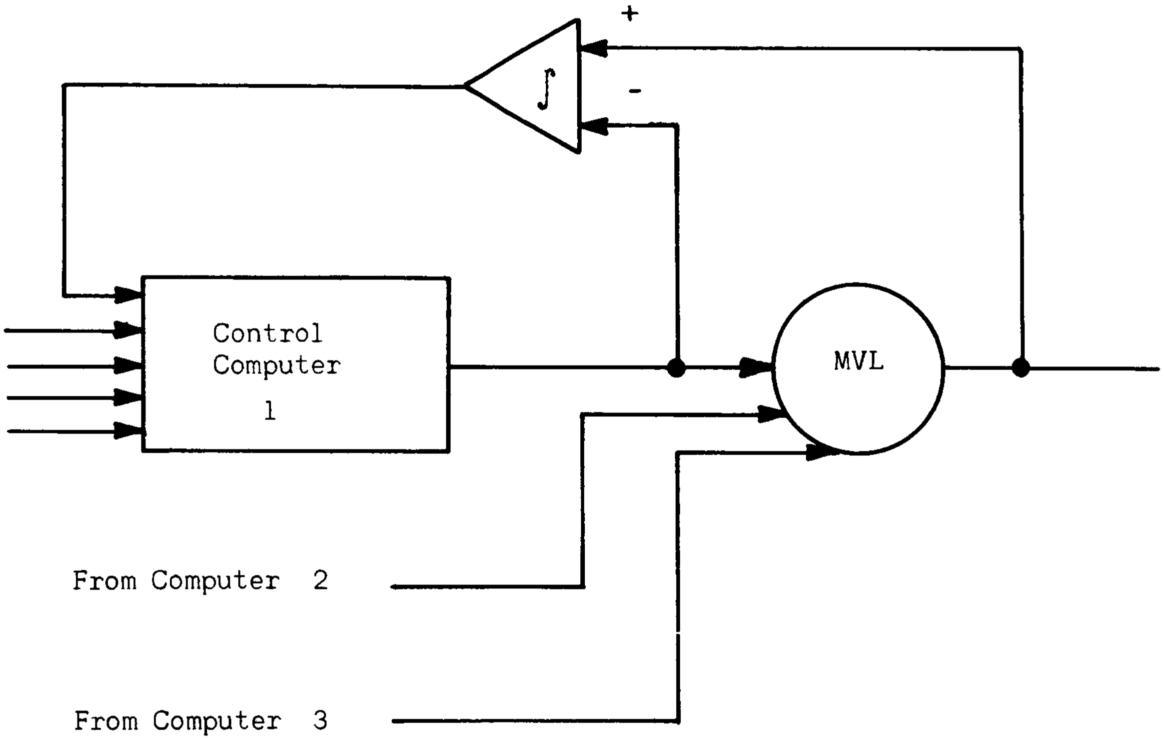


Figure 6-9
Equalization Technique Using Mid-Value As
Channel Slaving Reference

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