A PILOT'S SUBJECTIVE ANALYSIS OF A COCKPIT DISPLAY OF TRAFFIC INFORMATION (CDTI)

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SUMMARY

During recent years, aviation growth rates have been outstripping the ability of the air traffic control (ATC) system to effectively accommodate the ever-increasing demand. Human error has been found to be a casual or contributing factor in a large percentage of aviation accidents--both air carrier and general aviation. Recent accidents and incidents indicate the interface between the cockpit and the air traffic control system is a major problem area contributing to human error problems for both pilots and controllers.

Reduction in human errors may be achievable through better integration of the pilot into the information loop by the exploitation of recent technological advances. Both the advent of electronic displays for cockpit applications and the availability of high-capacity data transmission systems, linking aircraft with ATC ground computers, offer the opportunity of expanding the pilots' role in the distributive management process. A critical element in the distributive management process is believed by many to be the presentation to the pilot of his traffic situation, i.e., CDTI.

Although the CDTI concept has obvious potential benefits, it must be examined in an operational environment to assess the conditions under which the crew can effectively utilize it, the effect on controller procedures and efficiency, and the overall impact on system safety, efficiency, and capacity. As part of a joint NASA/FAA effort, CDTI flight tests were recently conducted with a research aircraft equipped with advanced cockpit displays.

This paper briefly presents the results of these flight tests and summarizes one of the test subject's subjective analysis of the CDTI concept.

INTRODUCTION

During recent years, aviation growth rates have been outstripping the ability of the air traffic control (ATC) system to efficiently accommodate the ever-increasing demand for capacity. One method that has been proposed to alleviate this problem is to provide traffic information in the cockpit to allow the pilot to interact more directly in the ATC process and thereby permit the use of more efficient procedures. This concept was first proposed during the 1940's (ref. 1). Early tests of this concept, however, involving TV broadcast of the controllers' radar scope, resulted in numerous deficiencies related to the mechanization scheme employed. Recent technological advances,

including the Discrete Address Beacon System (DABS), Beacon Collision Avoidance System (BCAS), and electronic display systems, have resulted in a resurgence of interest in exploring potential benefits to safety, efficiency, and capacity offered by such a concept.

Studies initiated during the early 1970's by the Massachusetts Institute of Technology, under Federal Aviation Administration sponsorship, provided initial exploration of traffic-situation display concepts in a simulation environment and demonstrated pilot acceptance of traffic information (ref. 2). More recently, a joint FAA/NASA program has been undertaken to explore potential cockpit display of traffic information (CDTI) applications through the use of full-system studies (i.e., the real-world environment would be closely approximated). A first step under the joint program was a study (ref.3) to obtain a set of guidelines for display content, symbology, and format that would be used for subsequent research, the general intent being to provide a basis for standardizing a display for use in follow-on CDTI experiments. That study, involving commercial airline pilots in group sessions during which static displays were viewed on a projection screen and rated, resulted in the definition of a preferred encoding scheme for depicting altitude and other information as part of the basic traffic symbol.

The primary objective of the present study was to assess the benefit of coded traffic symbology and to obtain an initial assessment of the impact of workload on pilot ability to monitor the traffic display, using simulated traffic in a flight environment. The coded symbology, based on the results of reference 3, was displayed on the pilot's electronic horizontal situation indicator (EHSI) and flight tested in the Terminal Configured Vehicle (TCV) research airplane. Workload variations were accomplished by use of two levels of airplane control automation. The tests consisted of 29 curved, decelerating approaches flown by research pilot flightcrews. The traffic scenarios involved both conflict and conflict-free situations. Subjective pilot commentary was obtained through the use of a questionnaire and extensive debriefing sessions.

THE CDTI CONCEPT

CDTI offers a possible means for providing the needed assurance for the pilot, as well as a possible means for providing a major breakthrough for improved operating efficiency through increased pilot participation in the distributive management of the ATC system. The CDTI concept is illustrated in figure 1, wherein a real-world situation is depicted, and a conceptual sketch of the CDTI is shown for the corresponding situation. As indicated by the sketch, CDTI is generally conceived to include not only traffic information, but also weather, terrain, and other map information required for navigation. Many believe it may ultimately provide the pilot with a capability equaling, or even exceeding, visual flight capability during instrument meterological conditions, in short, electronic VFR. On the other hand, there are some who believe it could lead to chaos, a sort of do-it-yourself ATC system.

RESEARCH SYSTEM

Research Airplane

These experiments were conducted in the NASA TCV airplane, a Boeing 737 jet transport modified for advanced control and display research. This research airplane is shown in figure 2 and described in reference 4. Principal features of the airplane, pertinent to this study, included the advanced cockpit environment provided by the aft flight deck (AFD) (fig. 3), from which a two-man crew could operate the airplane under instrument like conditions using electronic displays and a fly-by-wire control system.

Displays.- The primary flight displays for the AFD were monochromatic cathode-ray tubes (CRT), driven by the navigation/guidance and electronic display computers. Two CRT's functioned as electronic attitude director indicators (EADI); the two other CRT's functioned as electronic horizontal situation indicators (EHSI). They were located on the cockpit panel in the same general area as their mechanical counterparts (fig. 3). A description of the EADI is presented in reference 4. The EHSI, which measured 12.7 by 17.8 cm (5 by 7 in.), was basically a moving map display on which traffic information was superimposed to provide the CDTI for this study.

Control modes.- Two levels of pilot workload were achieved through the use of two flight control modes that were available in the TCV airplane. The higher level of workload corresponded to the use of the attitude control mode (ACM), which was essentially a rate command/attitude hold system. Specifically, the ACM provided a rate response proportional to control deflection whenever the control was positioned outside an electrical deadband, the center of which was defined by a mechanical detent. Within the deadband, the ACM maintained the commanded angle. The lower level of workload corresponded to the velocity vector control mode (VVCM), which was essentially a rate command/flightpath hold system. Like the ACM, the VVCM provided a rate response whenever the control was positioned outside the dead band. Within the deadband, however, the VVCM maintained both the vertical-flightpath and ground-track angles. Throughout the tests, speed was controlled using an autothrottle system wherein the crew manually selected the desired speed by use of a control panel.

Traffic Generation

The displayed traffic was generated from an onboard data tape which had been previously recorded using the Langley Real-Time Simulation System. Specifically, the traffic tape was created by using a piloted simulation capability, wherein approaches were made along each of the routes that corresponded to the airway structure prescribed by the test scenarios. These individual approaches were recorded and were then merged into a set of data that was both position and time correlated. Finally, the resulting data were geographically correlated and adjusted to match the runway and terrain configuration of the area of Wallops Flight Center where the flight tests were conducted. The output of these merged data was the representation of numerous airplanes following several flightpaths and landing with a nominal separation

of 2 1/2 n. mi. at the runway threshold. This traffic-generation technique was developed for use in the study described in reference 5.

CDTI DISPLAY FORMAT

General Format

The general format for the EHSI was a "track-up" display with a fixed own-ship symbol that was centered laterally on the display and was positioned longitudinally such that two-thirds of the viewing area was ahead of own-ship. A magnetic-course indication was presented along the upper portion of the display, and various digital information was shown in the lower corners (fig. 4).

A sufficiently high update rate was used so that motion of the EHSI map appeared to be continuous with respect to own-ship. Geographical-position updating of the traffic, on the other hand, was done at 4 second intervals in order to simulate the current terminal-area radar sweep rate.

The test subjects had direct control over several aspects of the CDTI. Of primary importance were the capability for selecting traffic data blocks and map-scale factors. The six map scales, ranging from 0.4 to 12.6 n. mi./cm (1 to 32 n. mi./in.), could be selected by using a rotary knob. (Because of limited computer capacity, independent selection of map scale for the captain's and first officer's CDTI displays was not possible.) The traffic-data-block option, which provided airplane identification, altitude, and ground-speed information, was selected by using a push button. Selection of this option caused the data blocks for all displayed traffic to appear simultaneously. The capability to select individual data blocks for specific traffic, as suggested in reference 3, was not available.

Traffic Symbology

In addition to tests with the coded traffic symbology, uncoded traffic symbols were used during tests to obtain a comparative evaluation. Both the coded and uncoded traffic symbology are presented in figure 5. The basic characteristic of the uncoded traffic symbol, based upon a previous (unpublished) TCV program investigation, is that ground-track angle is explicitly shown. The coded symbology explicitly identified altitude relative to own-ship, indicated whether the traffic was under ATC control, and indicated whether it was CDTI equipped. With regard to altitude encoding, an altitude band of $\pm$150 m ($\pm$500 ft.) was used to define "at" own-ship altitude.

Additionally, as shown in figure 6, the traffic symbology included a position predictor, position history, and an airplane data block. In all cases, the position history depicted airplane position for the three previous updates. The position predictor, for the coded-symbology case, was simply a velocity vector, scaled to represent either a 30- or 90- sec prediction, the longer prediction being used in conjunction with the 0.8 n. mi./cm (2 n. mi./in.) and

larger scale factors. For the uncoded-symboloby case, and for own-ship in all cases, the prediction vectors included roll-angle information.

Terminal-Area Route Structure

The overall route structure is shown in figure 7. The three routes indicated by the dashed lines were alternate arrival paths and were provided to represent a typical terminal area. The route indicated by the solid line was used by own-ship; it was based on an experimental Standard Terminal Arrival Route (STAR) developed for the TCV program. This route was designed to exploit the expanded coverage provided by advanced landing aids such as the microwave landing system (MLS). In addition to specifying the route, the STAR contained waypoints for which nominal altitudes and speeds were prescribed as shown in figure 8.

Traffic Scenario

Four traffic scenarios used in this study are shown in figures 9 to 12. In all the scenarios, which involved seven landing airplanes, own-ship was positioned to be fifth in the landing sequence. An eighth airplane was programmed to overfly the terminal area at a high altitude. The altitude and speed profiles were the same for all landing airplanes; they were specified as a function of ground-track distance from the runway threshold as specified in figure 8.

Figure 10 illustrates the general traffic arrangement, where the numerals designate the landing sequence for airplanes 1 to 7; airplane 8 is a constant velocity, constant altitude overflight of the simulated terminal area. The intended flightpath of airplane 8, unlike the STAR and the alternate routes, was not displayed. In an effort to provide additional realism, airplane 4 did not follow the proposed path exactly, but delayed its first turn, and then paralleled the desired path until it intercepted the straight-in portion.

Conflict-Free Scenarios

Two conflict-free scenarios were generated for this study, their differences being the initial position and flightpath of airplane 6. For scenario A, airplane 6 was positioned on one of the alternate routes (fig. 9) and was programmed to merge 2 1/2 n. mi. beyond own-ship in the landing sequence. For scenario B, airplane 6 was positioned on another of the alternate paths behind airplane 4 (fig. 10) and was programmed to follow the same flightpath as airplane 4, again merging 2 1/2 n. mi. beyond own-ship.

Conflict Scenarios

A conflict scenario was generated from each of the two conflict-free scenarios so that airplane 6 would violate own-ship's airspace. Scenario C,

the conflict situation derived from scenario A, was produced by adjusting the initial position of airplane 6 along its route, and then changing its flightpath to delete the last turn. This path and the point of conflict are shown in figure 11. The other conflict situation, scenario D, was created by adjusting the initial conditions of airplane 6 in scenario B and modifying its flightpath to a straight line (fig. 12.) In both conflict scenarios, the vertical path of the conflicting airplane was adjusted to coincide with the altitude profile of own-ship at the point of conflict.

RESULTS AND DISCUSSION

The results of this test can best be shown by putting the reader in the pilot's seat and systematically running through a typical curved approach to landing. The approach selected was previously described as scenerio C, which had a conflict situation materialize on base leg just prior to the turn to final.

The approach is started as shown in figure 13 with own-ship on downwind leg in straight and level flight at approximately 1524 m (5000 ft) with a ground speed of 209 knots and an airspeed of approximately 179 KIAS. Figure 13 shows own-ship to be 13 seconds from Waypoint MERCI which is the start of descent point. The wind at altitude is shown to be from 252^{o} at 26 knots. The map scale is shown as 1.6 n. mi./cm (4 n. mi./in.) and the aircraft is coupled in 4D for guidance. Four other aircraft can be seen, two below own-ship's altitude and one above. The fourth aircraft is landing on the runway. No conflicts are apparent at this time.

Figure 14 shows own-ship now under MLS coverage in a descending left turn on track both vertically and horizontally. Once under MLS coverage, the vertical and horizontal deviation tapes automatically appear. The horizontal situation is displayed in a track-up mode and as can be seen own-ship has made an approximate 90^{o} left turn. The current altitude is just over 823 m (2700 ft), the ground speed is 159 knots and the airspeed is approximately 171 KIAS. The scale factor has been changed to 0.8 n. mi./cm (2 n. mi./in.) and the guidance is still 4D. Three aircraft are shown on the display, only two of which have tracks which will intersect that of own-ship. The coded symbol of the aircraft closest to own-ship indicates that he is 152 m (500 ft) or more above own-ship's altitude. Without the airplane data block selected, nothing else is known about his vertical position. The coded symbol does indicate that he is not under ATC control and not equipped with CDTI. The other airplane with an intersecting path is within 152 m (500 ft) of own-ship's altitude, is under ATC control, but is not equipped with CDTI. The pilot's attention is naturally drawn to this airplane in the upper right hand corner because it can be seen that, even if he follows his intended flightpath, the spacing at the runway threshold is probably going to be close.

Figure 15 depicts the approach scenario approximately 50 seconds later. The pilot has called up the airplane data tags and immediately sees that the airplane closest to own-ship (DA 495) is indeed no factor because he is over-

flying the scenario at 2438 m (8000 ft). The real potential conflict is Trans World 80 (TW 080) because he has been descending at approximately the same rate and his altitude has been approximately the same as own-ship. If he follows his projected path the longitudinal separation will not be adequate when both airplanes arrive on the final approach segment. Own-ship's pilot has switched to 2 D guidance (horizontal only), has essentially stopped his descent and is commencing an early slowdown to final approach speed in order to increase both the horizontal and vertical separation between own-ship and Trans World 80. This is the logical thing to do because Trans World 80 is slightly ahead of own-ship and own-ship has no traffic immediately behind him.

Figure 16 depicts the scenario approximately 40 seconds later. The vertical separation between own-ship and Trans World 80 is now approximately 152 m (500 ft) with own-ship currently crossing his projected flightpath. It should be noted that the actual position of own-ship is the apex of the triangle. Trans World 80 has missed the turn to final and is currently tracking straight ahead through the scene at 488 m (1600 ft). On his present course he will pass behind and approximately 152 m (500 ft) below own-ship. The potential conflict has successfully been avoided. The pilot of own-ship has resumed his descent in order to recapture his vertical path. The EADI shows his gamma wedges below the -3.0^{o} reference line and the NAV Data page shows that he has a 2.1^{o} intercept angle established in order to recapture his vertical profile. The EHSI indicates in the lower left hand corner that he is still coupled in 2 D and is manually controlling the selection of Flightpath Angle (gamma) and Indicated Airspeed (IAS).

Figure 17 depicts the scenario approximately 50 seconds later. The pilot of own-ship has switched the EHSI to the 0.4 n. mi./cm (1 n. mi./in.) scale. All of the other aircraft have flown out of the area of coverage except for the airplane just short of the threshold of runway 22. The pilot of own-ship can now devote all of his attention to the task of recapturing his vertical profile, making his turn to final and assuring that his airplane is properly configured for landing. It can also be seen that when the 0.4 n. mi./cm (1 n. mi./in.) scale factor is selected only 30 seconds worth of trend vector extends from the nose of the own-ship symbol.

The NAV Data page shows the own-ship altitude at 379 m (1244 ft) with the altitude error decreased from 157 m (516 ft) in figure 16 down to 51 m (166 ft) in figure 17. The pilot of own-ship is still maintaining a flightpath angle error (FPAE) or vertical path intercept angle of just over 2^{o}.

Figure 18 depicts own-ship in a left 8^{o} bank turn to the final straight in segment of the approach. The EADI shows the aircraft at a radar altitude of 180 m (590 ft) and back on the path both horizontally and vertically. The flightpath angle is approximately 3^{o} below the horizon and the acceleration cue indicates a slight deceleration along this flightpath. The pilot has selected the speed error option and set the desired approach speed as a target. The dark bar seen on the left wing of the airplane symbol indicates that the current airspeed is slightly faster than the set approach speed. As the airplane slows the bar will decrease in height and disappear when on speed. If the airspeed decreases below the set approach speed the bar will appear below

the left wing of the aircraft symbol and function in the same manner. The perspective runway and extended center lines can also be seen moving into the picture as the aircraft progresses around the final turn. The perspective runway, with correct and accurate microwave or navigation signals, will exactly overlay the actual runway.

The EHSI also depicts Runway 22 in a planform view. The airplane at the far end of the runway is the airplane that own-ship has been following on the approach. It is not obvious from this photo but the autoland system has been armed, the glideslope has been captured and the localizer signal should capture as the airplane completes the final turn.

Figure 19 depicts own-ship at a radar altitude of 28 m (92 ft). The box around the airplane symbol in the EADI indicates that the autoland control laws have been implemented and the airplane is within Category II landing criteria at 30 m (100 ft).

Figure 20 shows the view out the front cockpit windshield with the airplane at approximately the same position on final approach.

Figure 21 depicts the airplane at 8 feet radar altitude. Both the pilot when flying manually, and the airplane automatics when flying a coupled approach commence the flare at approximately 15 m (50 ft) above the runway. In figure 21, it may be possible to see that the low light level TV has been switched on. The horizon line can be seen to exactly describe the real world horizon and the perspective runway can be seen to overlay just slightly right of the actual runway. The flare task is accomplished manually by simply bringing the flightpath angle wedges up to a point just slightly below the horizon line. The aircraft automatics perform the task basically the same way. A manual over rotation and resulting aircraft "float" in ground effect will be immediately evident because the flightpath angle wedges will raise to a point slightly above the horizon line.

The perspective runway and tracking guidance remain available to the pilot during runway rollout.

CONCLUDING REMARKS

A representative Cockpit Display of Traffic Information (CDTI) system has been presented as viewed from the pilot in the cockpit, and the research results from these flight tests have been presented in reference 6. The use of advanced controls and displays allows for presentation to the pilot, large quantities of information that he has not had before. It can be easily seen that with this large quantity of data available a fine line exists between the display of valid, necessary information and clutter.

Figure 22 presents three needs that the pilot in the cockpit must have in order for a CDTI system to work effectively, efficiently and safely. These are the need to maximize the lead time for detection, the need to quantify the vertical situation, and most importantly the need for total situational aware-

ness. The real challenge in the design of an operational CDTI system will be the satisfaction of these needs and the presentation to the pilot of all the necessary information, but only the necessary information, in a useable format in order to avoid clutter. Even though a reasonably large display was utilized in these tests, display clutter was the primary problem from the standpoint of information assimilation.

Some of the other specific conclusions drawn by the pilots particpating in the flight test are:

1. For both the coded- and uncoded-symbology cases, ample leadtime for detecting and resolving conflicts was provided by the traffic display.

2. Although it was generally felt that encoding the symbology improved the overall traffic information presented, some of the encoded information, specifically, CDTI equipage and ATC control encoding, was of little interest from a pilot's viewpoint.

3. The most beneficial element in the encoded symbology was altitude; it provided a convenient means for the pilot to formulate a three-dimensional assessment of the situation without continuously displaying airplane data blocks.

4. The additional task of monitoring traffic did not adversely affect the traditional pilot task, with traffic observation falling naturally into the pilot's normal scan pattern.

5. The 2 1/2 n. mi. nominal traffic separation, used during this flight test, does not appear to be the lower limit if something could be done to eliminate the wake vortex problem.

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6. Abbott, Terence S.; Moen, Gene C.; Person, Lee H., Jr.; Keyser, Gerald L., Jr.; Yenni, Kenneth R.; and Garren, John F., Jr.: Flight Investigation of Cockpit-Displayed Traffic Information Utilizing Coded Symbology in an Advanced Operational Environment. NASA Technical Paper 1684, July 1980.

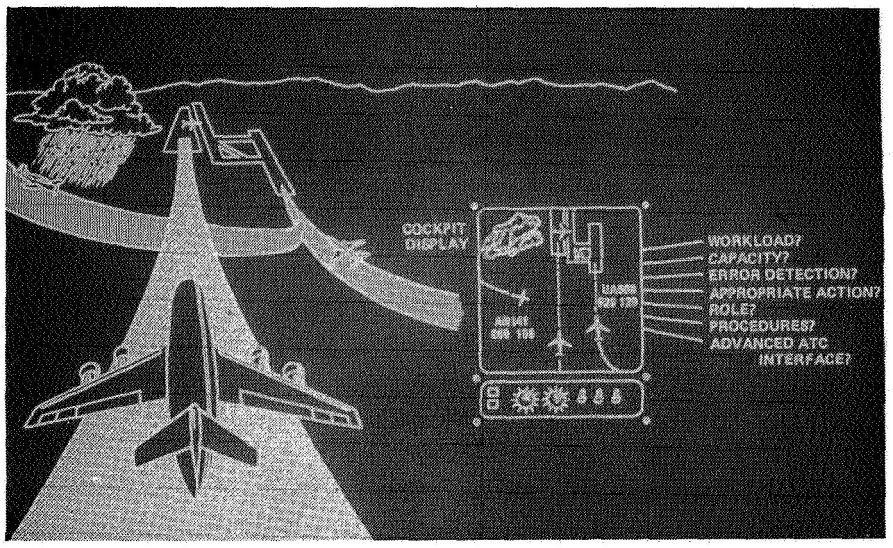

Figure 1.- CDTI concept.

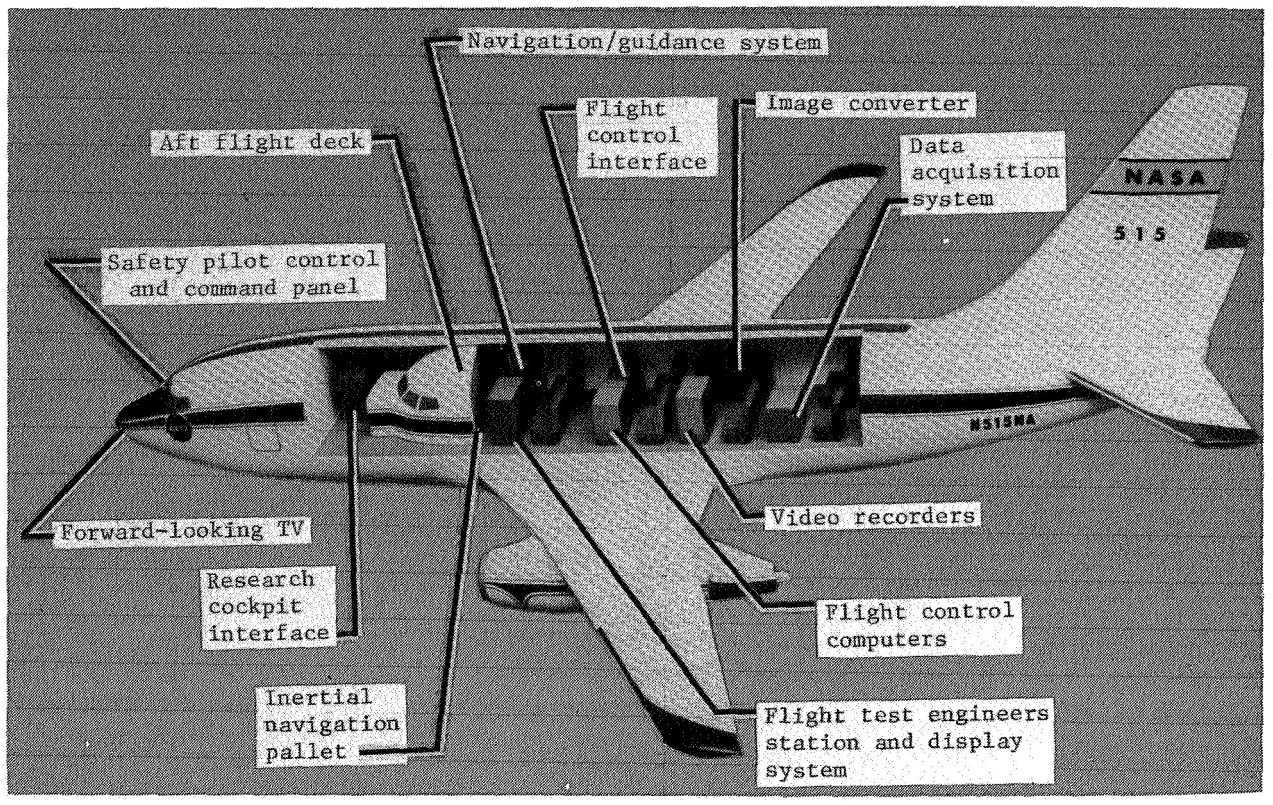

Figure 2.- Research airplane.

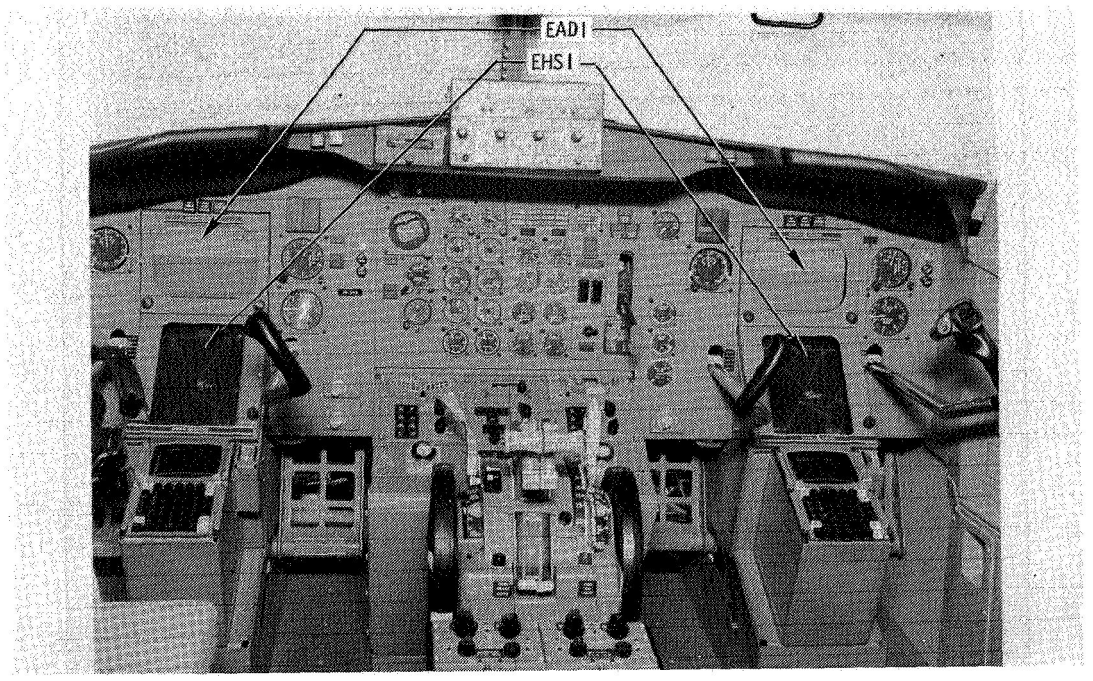

Figure 3.- Aft-flight-deck instrument panel.

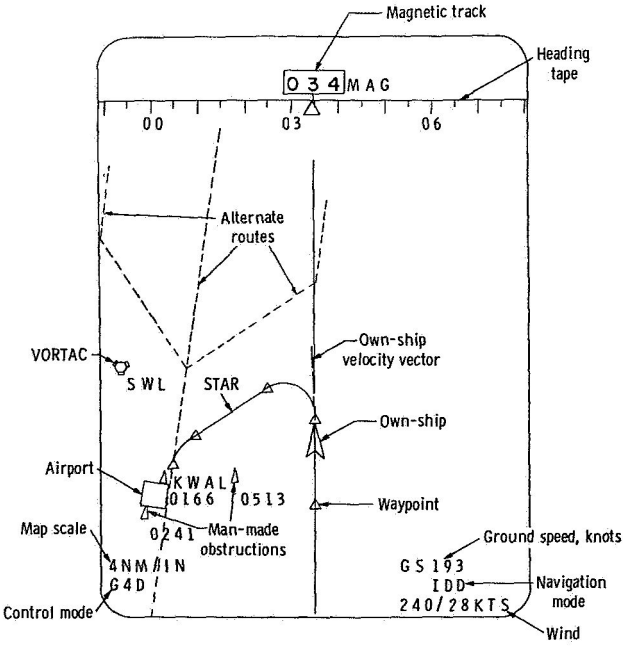

Figure 4.- Electronic situation indicator format. (1 inch = 2.54 cm.)

CODED

TRAFFIC	ABOVE OWN ALTITUDE	AT OWN ALTITUDE	BELOW OWN ALTITUDE
UNDER ATC CDTI			
UNDER ATC NO CDTI			
NO ATC NO CDTI			

UNCODED

Figure 5.- Traffic symbology.

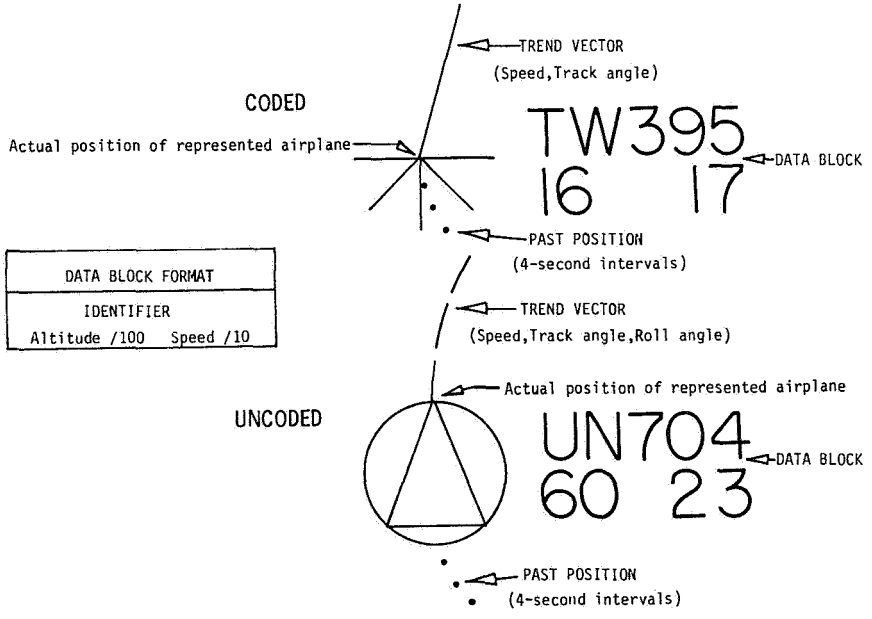

Figure 6.- Traffic symbology with situational information.

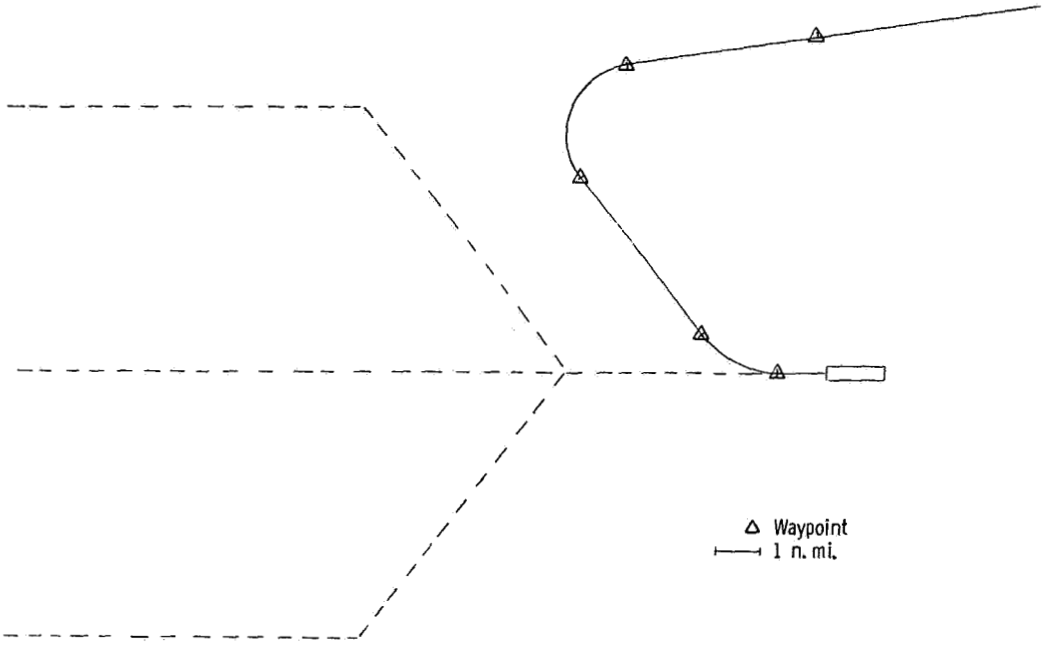

Figure 7.- Route structure.

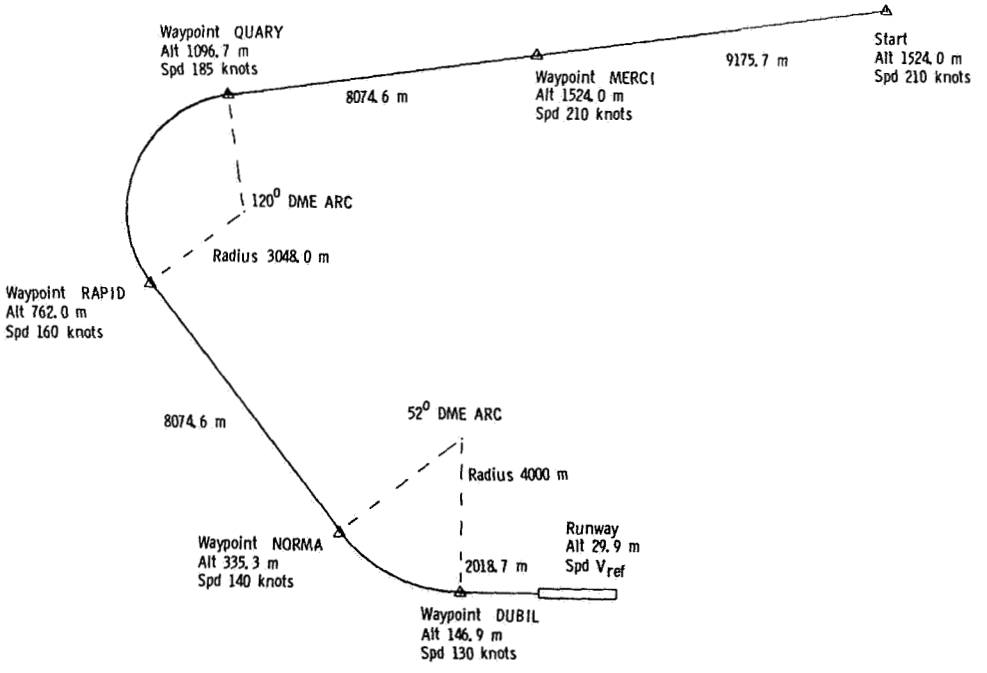

Figure 8.- Experimental standard terminal arrival route (STAR). (V_{ref} is reference velocity.)

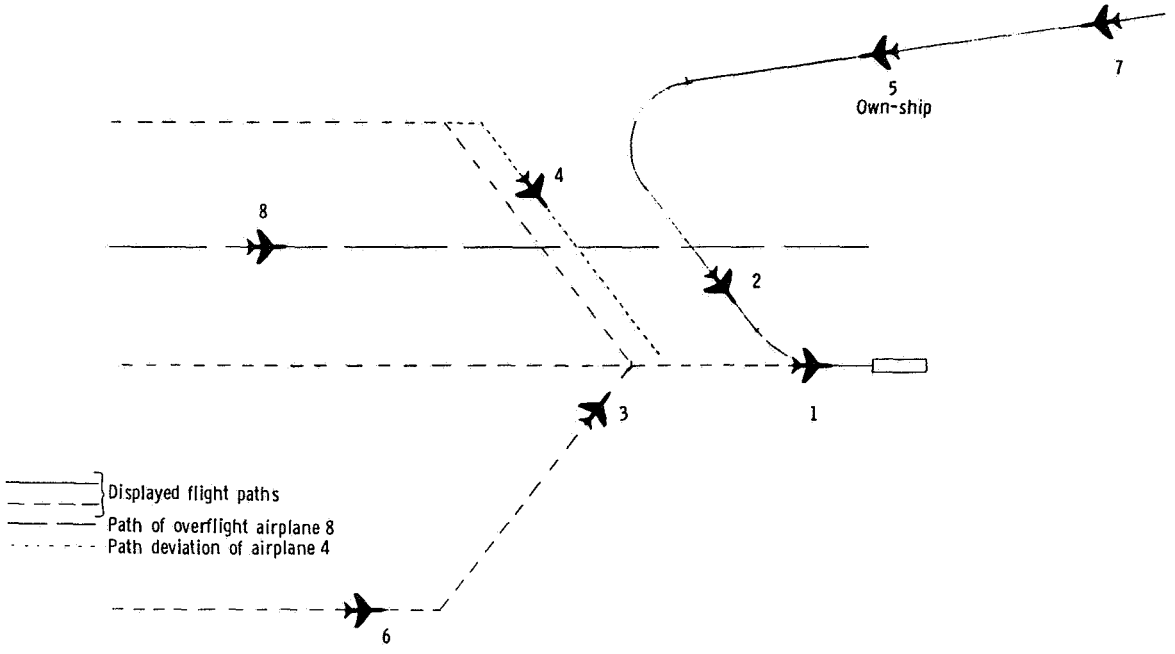

Figure 9.- Traffic scenario A.

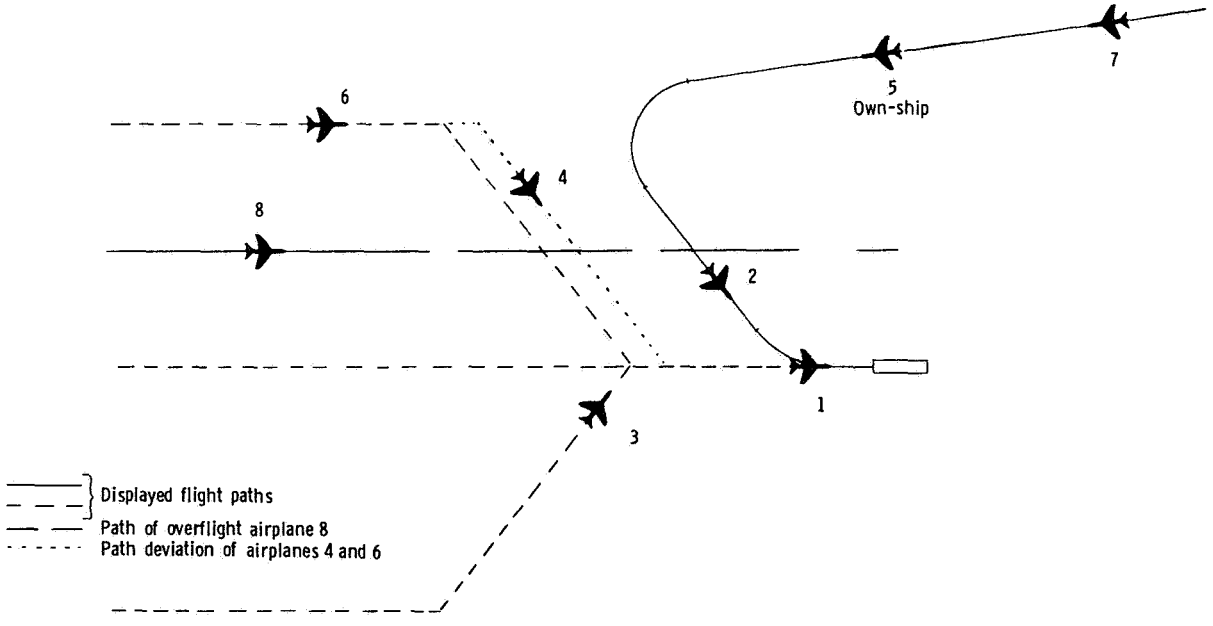

Figure 10.- Traffic scenario B.

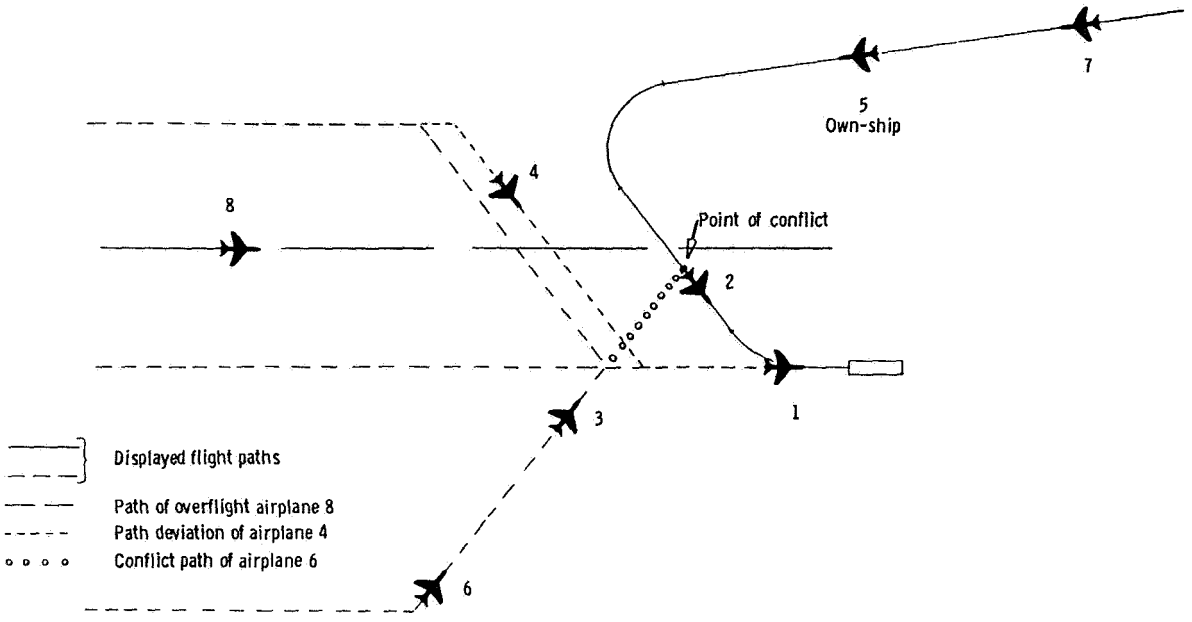

Figure 11.- Traffic scenario C.

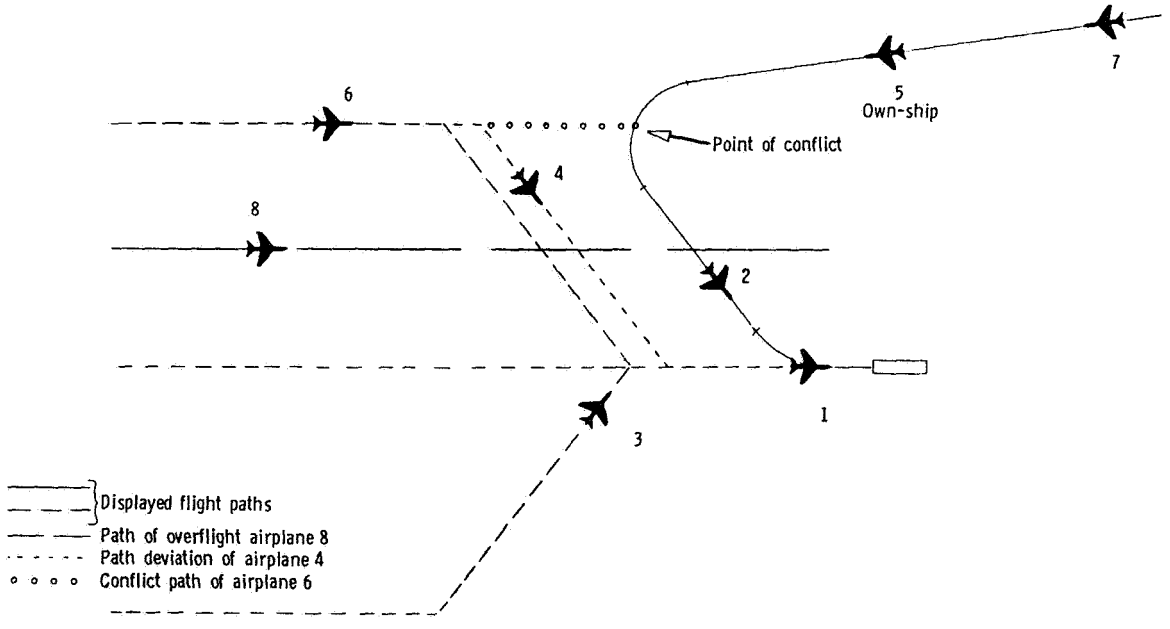

Figure 12.- Traffic scenario D.

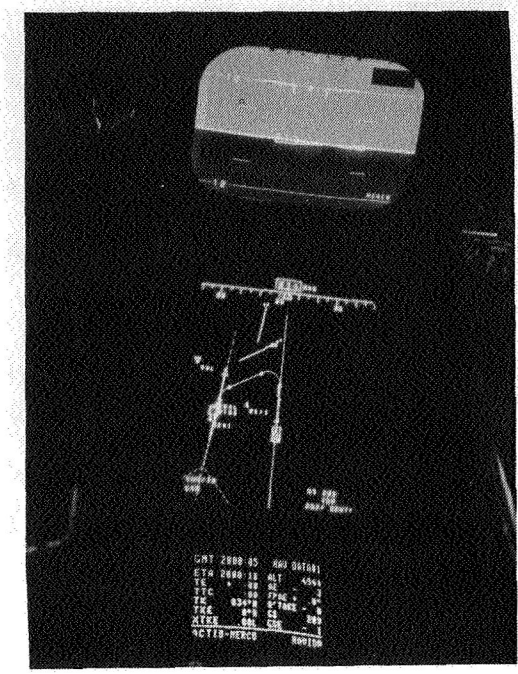

Figure 13.- Starting approach on downwind leg.

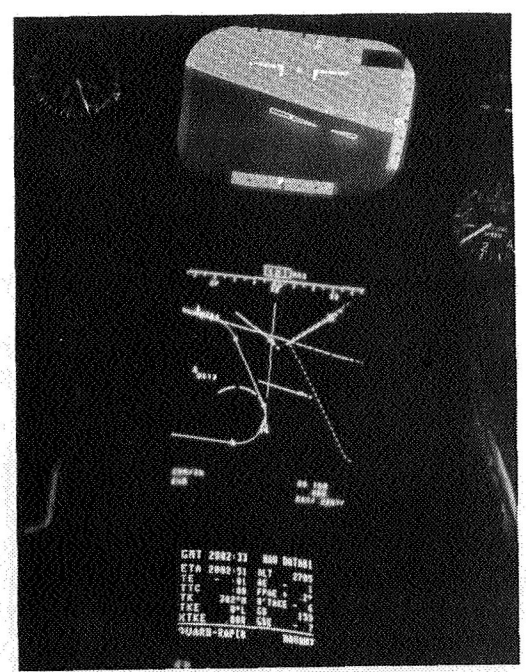

Figure 14.- Descending left turn to base leg. Potential conflict starts to become apparent.

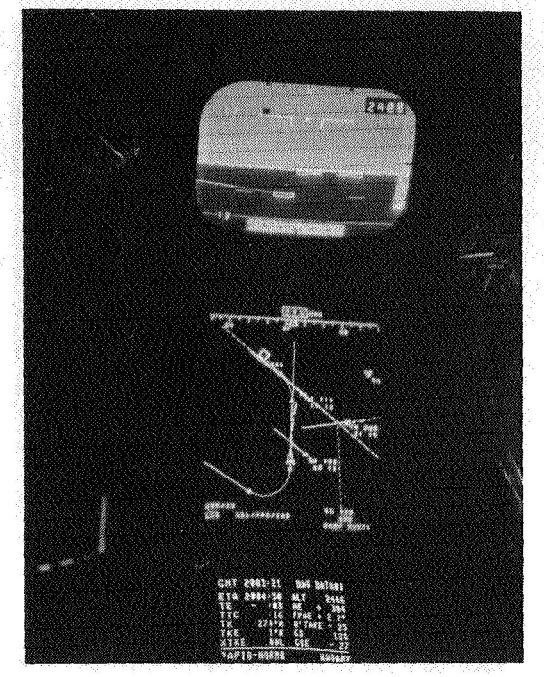

Figure 15.- Conflict imminent. Own-ship pilot levels and starts early slowdown.

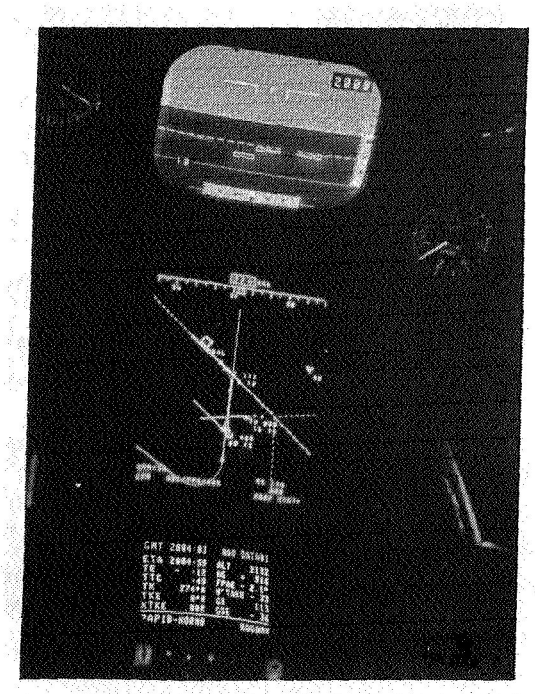

Figure 16.- Conflict avoided. Pilot resumes descent to recapture vertical path.

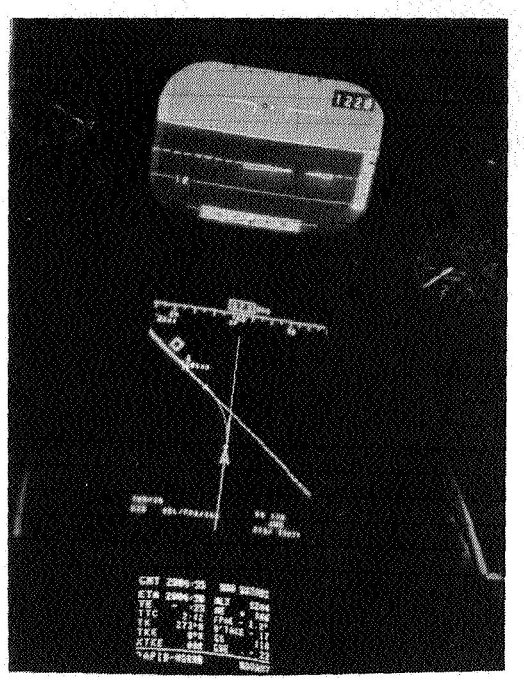

Figure 17.- Own-ship just prior to final turn. Vertical path capture imminent.

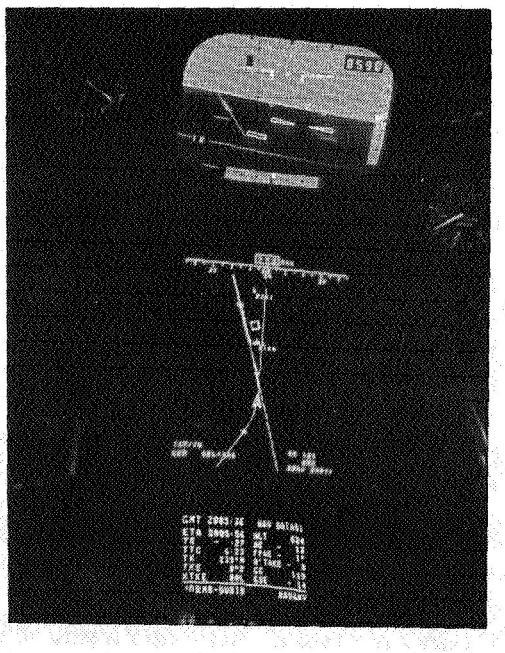

Figure 18.- Own-ship in left turn to final. Vertical path recaptured.

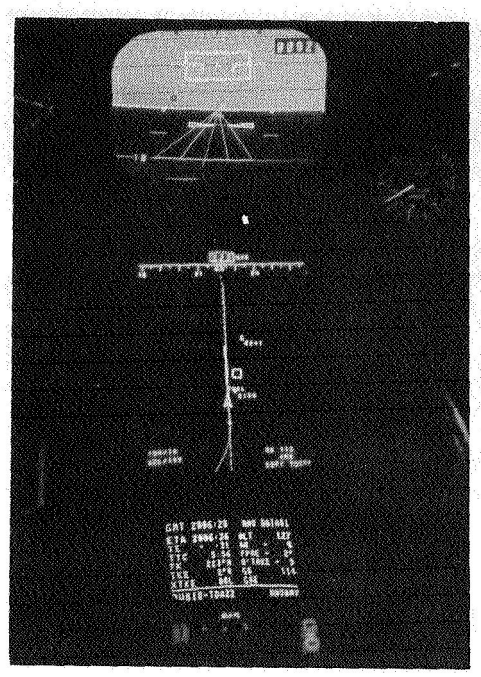

Figure 19.- Own-ship on short final. Autoland control laws implemented.

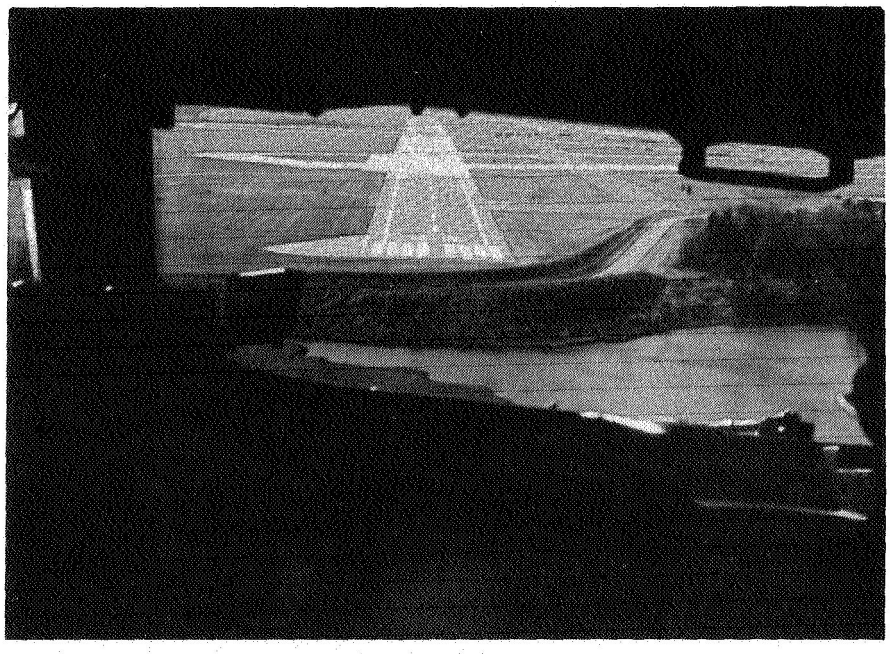

Figure 20.- View from front cockpit on short final.

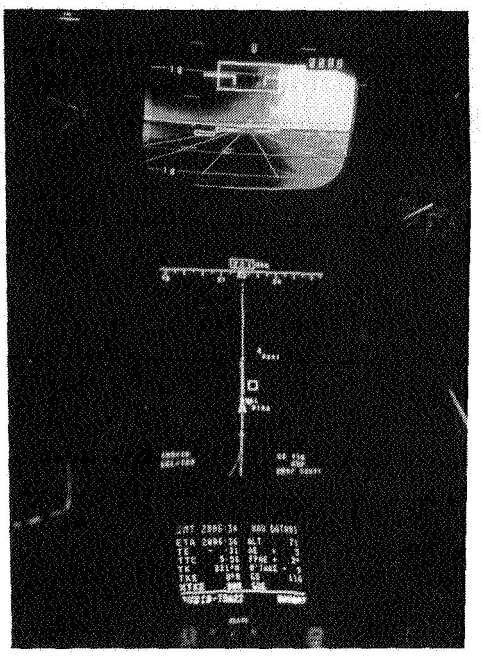

Figure 21.- Own-ship in the flare for landing.

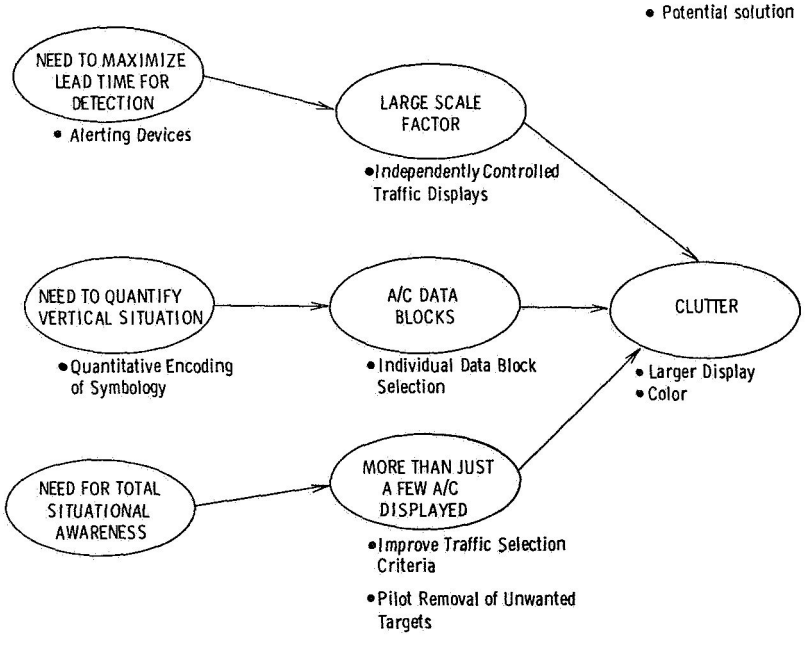

Figure 22.- Summary of display clutter factors.