CONCEPT DEVELOPMENT AND EVALUATION OF AIRBORNE TRAFFIC DISPLAYS

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ABSTRACT

A system concept for a cockpit traffic situation display (TSD) was developed and a preliminary evaluation was undertaken to investigate the effect of a TSD on safety, efficiency, and capacity in the 3rd generation NAS/ARTS ATC system environment. The optimum display configuration, examples of procedural changes, benefits to the pilot and benefits to ATC are discussed. The test program was conducted in three phases:

1. Basic tracking tests
2. ATC procedural tests
3. Spacing tests using position command data

Both quantitative and qualitative measures were used for determining safety, pilot and controller workload, and task performance. A comparison was made between operations conducted with and without a TSD.

Results of the test program were quite promising. Pilot response to the TSD as a safety device was strongly favorable. In tasks which involved limited pilot participation in the ATC control process, improvements in spacing accuracy and a decrease in communications at satisfactory pilot workload levels were demonstrated. Initial results indicate that additional research to fully explore the potential of TSD's should be undertaken at the earliest opportunity.

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LIST OF SYMBOLS AND ABBREVIATIONS

ADF	Low frequency navigation aid (automatic direction finder)
ARTCC	Air route traffic control center
ARTS	FAA terminal area data automation program
ASDE	Airport surface detection equipment
ATC	Air traffic control
ATIS	Automatic terminal information service
ATR	Airline transport pilot rating
CAS	Collision avoidance system
CAT II	Second stage of FAA low visibility landing program — permits landing operations down to 1200 ft visibility
CF1-A-I	Certified flight instructor-airplane-instrument
COMML	Commercial pilot rating
CRT	Cathode ray tube
CWS	Control wheel steering
D/A	Digital to analog
DOT	Department of Transportation
DME	Distance measuring equipment
EPR	Engine pressure ratio
FL	Flight level
GT	Ground track
HSI	Horizontal situation indicator
IFR	Instrument flight rules
IAS	Indicated airspeed
ILS	Instrument landing system

INST	Instrument rating
NAS	FAA enroute data automation program
PWI	Proximity warning indicator
R-NAV	Area navigation
SEL	Single engine land rating
SELS	Single engine land and sea rating
SID	Standard instrument departure
SMEL	Single and multi-engine land rating
STAR	Standard terminal arrival route
TRACON	Terminal radar approach control
TSD	Traffic situation display
TVOR	Terminal VOR
VFR	Visual flight rules
VOR	VHF navigation facility (VHF omnidirectional range)
R_{st}	Range between subject and target aircraft
T_{acq}	Time to acquire 90% of the required spacing
$\Delta V_{g/s}$	Velocity difference (based on ground speed data)
V_{IAS}	Indicated airspeed
θ_{CMD}	CWS pitch command
ϕ_{CMD}	CWS roll command
σ	Standard deviation

A key for interpretation of symbols used in radio navigation charts may found in Reference 4.

CHAPTER 1

INTRODUCTION

Major changes in the air traffic control environment must occur during the next decade if aviation's growing needs are to be met. Many of the present weaknesses in the ATC system will be addressed as planned additions to the national airspace system, such as improved surveillance, area navigation, microwave landing systems and data links are introduced into service. However, it still appears that these systems will not completely solve the problems of capacity, safety or workload. Additional means will have to be found to augment performance of the basic ATC system. Present efforts to meet this need are concentrating on development of ground-based, computer-assisted spacing techniques, collision avoidance or proximity warning devices, upgraded beacon surveillance capability and a variety of other systems.

1.1 System Concept

One concept for increasing performance and safety within this ATC environment, which has received little attention, is to provide aircraft with cockpit displays which present traffic information in a format useful to the pilot. The purpose of a traffic situation display (TSD) is to extend the visual senses of the pilot in such a way that operations could be conducted in instrument conditions in much the same manner that IFR operations are presently conducted in good weather. Through such a system, high capacity procedures, similar to visual approaches or vectors to the traffic pattern, could be employed in any type of weather and much of the capacity which is presently lost when weather is bad could be recovered. Such a display would serve to tighten the aircraft-pilot-ATC control loop so that response time to clearances or emergencies could be reduced thus permitting increased safety at reduced lateral or longitudinal separations.

TSD's potentially can play an important role in central, cooperative, or distributed management ATC systems. The utility of a traffic situation display need not be limited to a particular ATC concept. Similarly, the benefits do not specifically depend on the character of the data acquisition system. Either ground derived and processed ATC data which is transmitted to the aircraft, or airborne sensor data could be used to generate a TSD picture. If ATC processed data is used, any one of a variety of surveillance systems ranging from ground radars to satellites may serve as the basic input.

Since, however, the basic configuration of ATC for the coming decade has been established, present research has been directed toward investigation of the use of traffic situation displays within the ground based, centrally managed, third generation ATC system. A TSD is not intended to provide "self contained" air traffic control capability. It, also, is not envisioned as a substitute or replacement for any particular instrument or system. Rather, it may serve as a device to enhance the capability of CAS, PWI, computer spacing or other systems.

The concept of providing traffic information in the cockpit has been proposed in various forms for many years. However, it has been only recently that advances in technology have made its construction at a reasonable cost, feasible. Accordingly, this thesis attempted to reexamine the concept of a TSD. The three main research objectives were to:

1. Outline a system concept for providing a sectorial display of traffic in the cockpit,

2. Specify the parameters which should be considered in the design of the cockpit display, and

3. Evaluate the potential of a TSD for improving safety, efficiency or capacity in the NAS/ARTS ATC environment.

1.2 Hardware Description

A functional diagram showing the ground and airborne hardware associated with a NAS/ARTS based cockpit traffic situation display system is shown in Figure 1.1.

Primary and beacon surveillance radars provide basic data to the computers in the air route traffic control centers and approach controls. This basic data is processed along with flight plan information and used to generate the ATC controllers displays. With limited reprocessing and formatting, portions of this basic data could be broadcast on a common radio frequency to aircraft within the facilities area,to serve as the data base for a cockpit traffic situation display. Transmission would be via VHF digital data link. Studies indicate[1] that the data required to service 100 aircraft in a terminal environment could be handled by an 8 kilobit/second transmission rate. This would provide a complete traffic picture including target positions, identifications,altitudes (for mode C beacon equipped aircraft), selected map information, and ground weather radar contours (if desired) every four seconds. This data rate can be accommodated in a 25 KHz VHF channel.

Aircraft equipped to receive the data link broadcast would use a small airborne computer to select appropriate information from the data stream, process the data according to the settings on the pilot's display

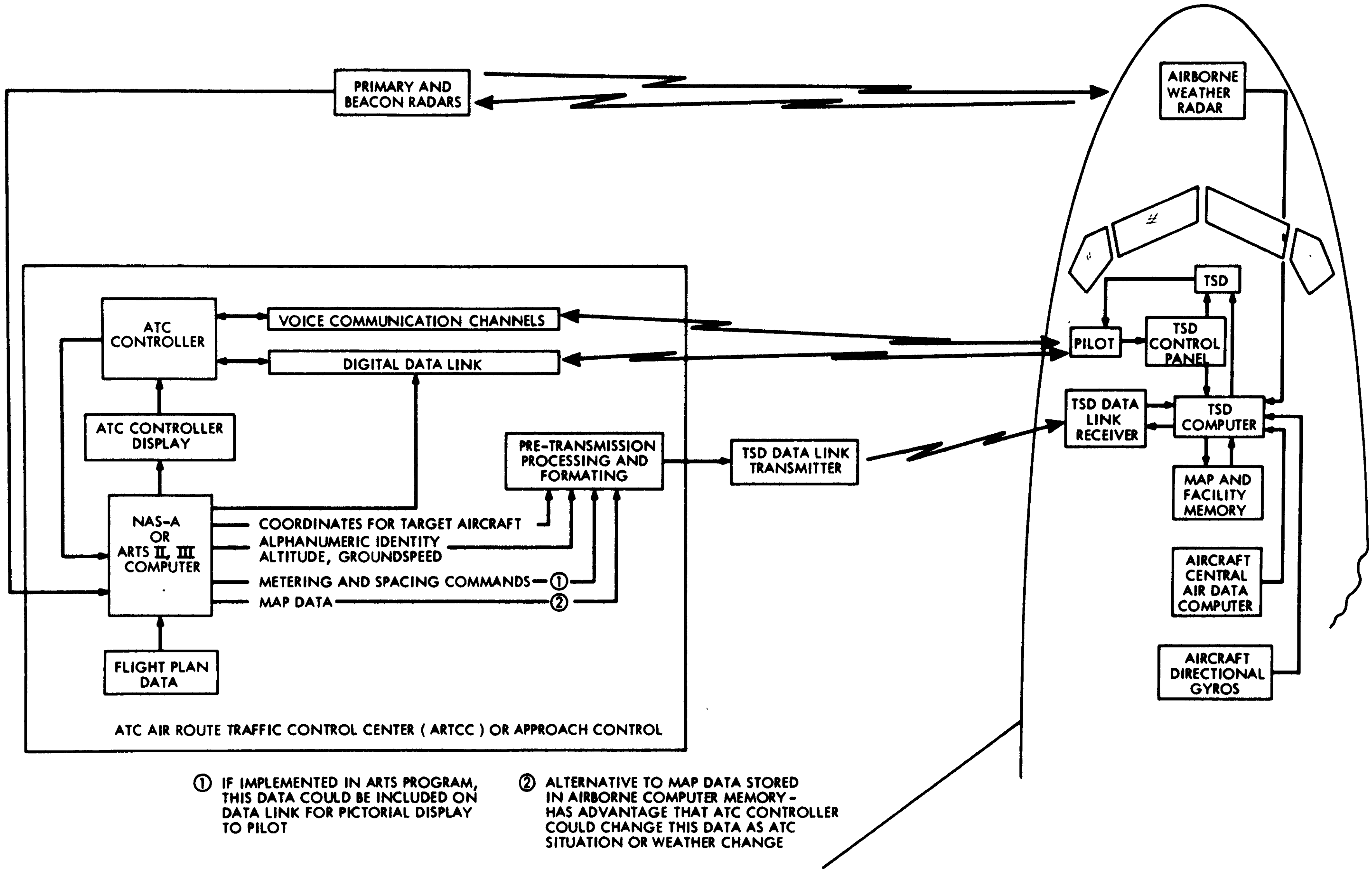


Fig. 1.1 Traffic Situation Display System Diagram

controls, and generate the TSD picture. Other inputs to the TSD computer would be:

1. Aircraft heading from the directional gyros — used to orient display.

2. Memory data — used to generate portions of the background map which do not change frequently, also stores data link frequencies for automatic switching, etc.

3. Airborne weather radar system signals — processed and displayed on TSD at the appropriate range scales.

4. Central air data computer (CADC) signals — provides own aircraft's altitude, velocity, identification, etc.

Inputs from airborne vortex turbulence sensors or clear air turbulence detectors could be included on the TSD as they become available. If beacon surveillance system coverage is extended to the airport surface and appropriate data is fed to the ARTS computers, TSD systems could provide a continuous display throughout the complete final approach, landing, and taxi. Such capability could be achieved by adding airport surface detection radar (ASDE) or other sensor inputs to the ARTS computer data base.

An additional feature which could be included in a TSD system is the uplink of graphical controller instructions. Through the use of a light pen or keyboard,controllers could draw vectors on their own display scopes representing nominal path or amended routings and have these simultaneously transmitted to all or selected aircraft in the system. This capability could add significantly to the flexibility of the ATC system. It would give the controller a powerful tool to deal with perturbations in the ATC system due to emergencies, weather, or other disturbances.

CHAPTER II

CONCEPT DEVELOPMENT AND EVALUATION

2.1 Goals

An experimental program was undertaken to investigate some facets of the traffic situation display's potential contribution to ATC safety, efficiency and capacity. The objectives of the program were to evaluate a TSD in a realistic environment through simulation in order to:

1. Optimize the display configuration.
2. Determine non-procedural potential benefits of a TSD to both pilots and ATC in the NAS-A/ARTS III environment.
3. Test and evaluate certain new ATC procedures based on a TSD which could increase efficiency and capacity of the ATC system. This is described in Chapter IV.

From the outset, it was realized that evaluation of non-procedural benefits of a TSD, such as pilot assurance and safety, would be difficult. Quantitative measures for these factors do not exist. Pilot assurance is often attributable to the existence of alternative courses of action. A feeling of safety is based on a pilot's confidence in the ability to maneuver his aircraft to successfully cope with unusual or emergency situations. If a TSD can clearly define existing alternatives or provide new alternatives, pilot assurance and subjective assesment of increased safety will probably result.

Rigorous treatment of this question requires extensive operational experience in an actual flight environment. However, it appears feasible to survey this field by using simulation and qualitative measures.

To enable pilots to evaluate a TSD's non-procedural benefits, a set of cases was devised which would both give pilots experience using the display and a chance to build confidence in its capabilities. Subject pilots qualitative evaluations were the primary source of data for this section. Questionnaires were used extensively and subject impressions and comments were solicited throughout the test program. Pilot extrapolation of simulation experiences to the real world was encouraged.

Evaluation of new procedures was accomplished in both quantitative and qualitative terms. The results are described in Chapter IV.

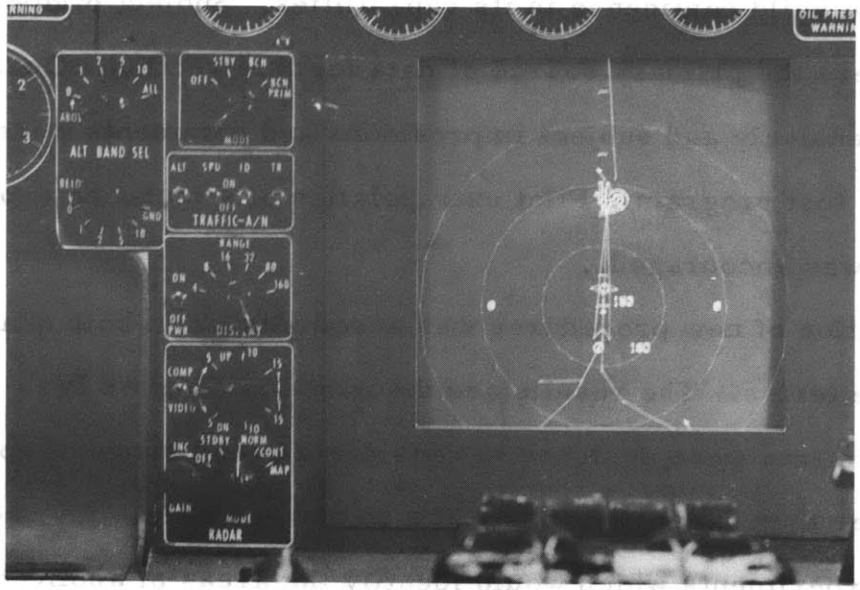
Experiments were designed to consider a broad range of applications of a TSD rather than exhaustive study of a particular area. An attempt was made to use experiments which would identify the areas of application for a TSD which appear most promising for further research.

2.2 Development of Display Configuration

To provide maximum benefit to the pilot, particular attention must be devoted to design of TSD format and content. Information on a TSD must be useful, appropriate to the phase of flight, and easy to intepret. Display clutter should be kept to a minimum. TSD controls must provide the necessary flexibility without being too complicated or confusing.

A desirable TSD configuration from a pilot's point of view was determined through experimentation with many display and control options in a simulated flight environment. The final configuration for display format and for the display control panel used in these tests is shown in Fig. 2.1.

Because the standard frame of reference used by pilots for orientation is based on aircraft axes, it was decided that the TSD picture should be oriented in such a way that up on the display corresponds to aircraft heading. This enables pilots to interpret azimuth data in terms of the "natural" coordinate frame of clock positions or relative bearing. The experimentation indicated a strong preference for this display configuration by subject pilots.



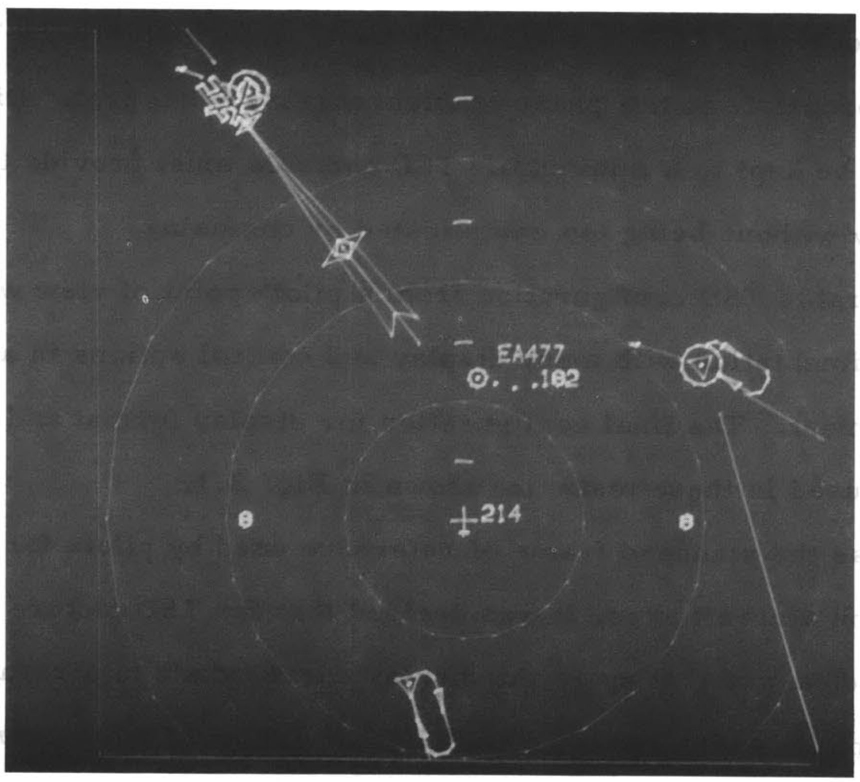


Fig. 2.1 Traffic Situation Display and Control Panel

If a fixed, north up oriented display is used, map data can be interpreted normally but correlation of display data with outside references is much more difficult. If the fixed, north up display is used for maneuvering, information regarding other aircraft bearing and heading is often misinterpreted. Disorientation may occur when flying south while using a north oriented map.

Rotation of the map with respect to aircraft heading should be continuous as the aircraft changes heading. The map should translate with respect to the subject aircraft's position. This results in the symbol for the aircraft being always fixed in the same position on the display while the background map and targets translate as the data is updated. If no position smoothing between updates is used, translational jumps of the background map and traffic occur due to the radar scanning rate. The following configurations of update rate and smoothing were tested and found satisfactory:

1. continuous translation of map and targets — (corresponds to predicting and smoothing of data received at the 1 or 4 second update rates.)

2. 1 second map and target translation update — (corresponds to increased data rate of advanced surveillance systems.)

3. 4 second map and target translation update — (corresponds to updating the data for each radar antenna sweep.)

Continuous translation, as may be expected, was the preferred configuration. However, it appears that pilot acceptance and performance are relatively insensitive to update rate as long as the magnitude of the jumps are small compared to the physical size of the display at the range scale which gives the largest resolution (the smallest number of miles per inch on the scope). Pilots generally felt that the 4 second jumps were quite acceptable.

In fact, in some circumstances, the jumps are desirable because relative motion is easier to perceive. With continuous translation, targets must be watched closely for a few seconds to note the direction and magnitude of translation relative to own aircraft. (This effect must be distinguished from translation relative to a ground reference frame which is determined from observing target heading or ground track.)

Since more viewing range is preferred ahead of the aircraft than behind, the subject aircraft symbol was placed so that 2/3 of the available display range was forward and 1/3 after.

Scope size is determined by overall legibility in representative congested traffic situations, resolution capability in terms of nautical miles of viewing range per inch of display scope at the minimum range scale, alphanumeric character size and availability of space in transport aircraft cockpits. Although experimentation showed that performance was not significantly degraded when using small display scopes,[2] pilots expressed a strong preference for the larger versions. The final choice of display scope size was 7 1/4" high by 7 1/4" wide. It was felt that this size display was the largest which could easily be accommodated in present generation transport aircraft and about the smallest scope that pilots could readily interpret without complaint.

The traffic situation display was tested in the weather radar scope's present position because this space represents the most likely area in which a TSD would initially be tested. Pilot comments indicated that as vertical tape instruments are introduced for systems instruments and as more space becomes available in the newer generation aircraft cockpits, the TSD should be moved closer to the primary flight group instruments.

Eventually, traffic information such as provided on the TSD may be incorporated in advanced flight instruments as part of a CRT pictorial situation indicator which also includes gyro data, area navigation displays, moving map, and weather contours. Such a display would replace a number of instruments currently used and would be located in the general area now occupied by the horizontal situation indicator (HSI).

2.3 Display Controls for the TSD

The TSD control panel was designed with the intent of giving the pilot a large measure of flexibility in using the display without making the TSD controls functions unnecessarily complicated. An attempt was also made to provide a means to keep scope symbol clutter to a minimum.

The final version of the display control panel has provisions for range selection, alphanumeric tag selection, altitude reporting beacon discrimination, and an altitude band selector.

Range scales from 4 nm. to 160 nm. forward viewing distance can be selected as appropriate to the phase of flight. The 4 nm. scale is useful for precise maneuvering with respect to other aircraft and for monitoring close lateral and longitudinal separations. The 8 and 16 nm. scales are primarily used for coarse maneuvering in the terminal area. The 32 nm. scale provides a convenient display of the overall terminal area traffic situation. Larger scales, in general, are useful for monitoring high altitude enroute traffic situations, traffic detours around significant weather and gross views of terminal area traffic congestion.

The 8 nm. forward range scale seemed most appropriate for collision threat detection in terminal areas. If targets closed less than 4 nm., range scale was decreased to get a better view of the threat. Frequently, when short range scales were being used, pilots would momentarily select a larger range scale to get an overall traffic picture, then return to the original scale. Enroute, much greater range scales were used, depending on desired warning time with high closing speeds. To eliminate parallax, range rings were included on the CRT through software. To minimize distraction, range rings were displayed at a lower intensity than other features of the display. For some tasks, it is desirable to provide a variable range cursor which can be digitally set to an arbitrary mileage value. This eliminates the necessity for interpolation between range rings and increases the accuracy of reading the display if non-integer ranges were to be used for such tasks as maintaining spacings behind other aircraft.

An altitude band selector is used to restrict the display of targets to those within an altitude band of interest to the pilot. The vertical extent of this altitude band is adjustable by the pilot. The band is defined with respect to the subject aircraft. If the subject aircraft climbs or decends, targets will appear as they enter the band and disappear as they exit the band. For example, an aircraft at FL350 with TSD altitude band selector set at 2000' above and below would see only those targets which are at altitudes between FL370 and FL330. Targets above and below this range would not be displayed unless the subject aircraft climbs or descends. This feature greatly reduces scope clutter by restricting the number of targets which are displayed at a particular time. In rapid climbs or descents, pilots would generally set the controls so that adaquate altitude coverage would be provided to protect against aircraft "popping up" nearby without sufficient warning. The extent of altitude protection was based on rate of climb/descent, the number of targets in the area, and the amount of advance warning which the pilot desired. Since the altitude discrimination capability is applicable only to targets which have altitude reporting transponders or have flight plan data recorded in the ground computers, a control has been provided to eliminate targets for which altitudes are unknown. This feature could be used to eliminate these targets from the display when the subject aircraft is operating in positive control airspace. This feature would be most useful for eliminating primary and VFR beacon targets from the display when the subject aircraft is operating at high altitudes.

The set of alphanumerics associated with a traffic display which is useful to the pilot is limited to: (1) radar-track-based ground speed, (2) identity, (3) altitude and (4) target aircraft track. Track information should be displayed through directional symbols or past position tracers. The directional symbols give a less cluttered display, but tracers give an analog presentation of velocity through the spacing of the individual dots of the trace. The best configuration appears to be use of both directional symbols and tracers, with the option of eliminating tracers if the display becomes too cluttered.

Alphanumeric tag clutter is kept at a minimum by use of on-off switching. This permits pilots to display only information which is pertinent to the phase of flight. It was found that the alphanumeric speed tags were displayed most of the time. When large numbers of targets were present on the scope, identity tags were usually displayed only for initial identification of a particular target. Display of altitude tags largely depends on congestion and the phase of flight. It is felt that additional data relating to target aircraft will have little additional benefit considering scope clutter and pilot interest. Elimination of any of the features which have been outlined (for cost reasons or otherwise) will definitely decrease the utility of the display from a pilot acceptability or performance capability point of view.

After completing the test program, subjects were given a questionnaire which considered physical characteristics of the display. The results are shown in Table 2.1.

2.4 Map Information for A TSD

Although not intended as an area navigation display, a TSD should include limited map information. A basic map serves as a reference frame for evaluating target information. Much lead information is gained on target behavior by observing target progress relative to airways, nominal approach routes, navigation facilities or waypoints. This is especially true for targets which are maneuvering in the terminal area.

It is felt that the following four options should be provided as the basis of the map display.

1. high level airways,
2. low level airways,
3. terminal area arrival routes (STARS + Transitions), and
4. terminal area departure routes (SID's + Transitions).

A map, appropriate for the particular phase of flight, should be selectable at the pilot's discretion. Data which should be included on each of the four maps is listed in Table 2.2.

Although much information regarding obstructions, restricted areas, noise abatement procedures etc. could be included on the display, it is felt that information in addition to that listed in Table 2.2 would be of limited value in conventional IFR operations.

Table 2.1

Results of Display Survey

	Response to Alternatives
By Percentage	
	1. Display scope size was:
0%	A. too small
100%	B. about right
0%	C. too large
	2. Location of the display (position in cockpit) is:
70%	A. satisfactory
30%	B. should be closer to primary flight instruments
	3. Overall readability of scope (alphanumeric symbols, clutter, orientation, intensity) was:
77%	A. good
23%	B. acceptable
0%	C. poor
	4. Display controls panel is:
93%	A. useful and easy to understand
0%	B. useful but confusing
7%	C. more complicated than necessary

Table 2.2

Recommended Graphic Map Data
Symbols to be included on high level and low level maps:
— airway centerlines — key navigation facilities and waypoints — delay and holding fixes
Symbols to be included on terminal area arrival and departure routes.
— SID's and transitions (departure) — STAR's and transitions (arrival) — key navigation facilities and waypoints (arrival and departure) — holding fixes (arrival) — primary airport symbols which include runway orientation. (arrival and departure) — final approach course for ILS, VOR, ADF or R-NAV approaches including initial and final approach fixes — missed approach routings (approach)

A feature which should be included on the display is the ability of the pilot to control alphanumeric selection of map data. A set of controls should be provided to permit selective display of identification tags for items listed in Table 2.3.

Table 2.3

Recommended Alphanumeric Map Data	
ITEM	EXAMPLES
— airways and procedures	J 121 ACTON ONE ARRIVAL
— key waypoints and fixes	MILLIS BOS
— important inbound/outbound headings or courses	035^{o}HDG 121^{o}-R

Identification tags enable the pilot to positively identify routes, procedures and fixes so that proper correlation with enroute and approach charts can be accomplished.

Every effort should be made to ensure simplicity and freedom from clutter in the design of the map features of this display.

TSD maps at this time should not be designed to replace enroute radio charts and approach plates as a source of information regarding radio frequencies, procedures, minimum enroute altitudes, obstructions and the numerous other details which are required for IFR flight.

Map data can be provided in several ways including storage in an airborne computer memory or transmission via the TSD data link.

If possible, the CRT used for the TSD should be able to display weather radar data from either airborne or ground equipment.

2.5 Channel Selection

Regardless of which map, traffic, or alphanumeric options are included on a TSD, efforts should be made to keep cockpit workload associated with management of a TSD at a minimum. Station or channel selection methods must be chosen carefully. Most likely, a method will be needed to automatically control TSD frequency selection. The following alternatives are suggested.

Data link frequencies could be preprogrammed before takeoff, as is presently done with waypoint selection on inertial navigation systems, and changed in flight by an execute command entered manually. Alternatively, the execute commands could be coupled with navigation or communication frequency selection. As a predetermined frequency for navaid was selected, the TSD would automatically switch channels to the preprogrammed frequency which corresponded to the navaid which was chosen. Another method of switching would make use of paired radio frequencies. The same procedures which are applied to DME channels being associated with VOR frequencies for automatic switching, could be applied to TSD control. In this case, TSD frequencies would be matched with navigation or communication frequencies so that selection of a nav/com frequency would automatically control TSD station selection. If communication frequency pairing is used, an appropriate ARTS TSD data channel would be provided when approach or departure control frequencies were selected, and NAS TSD data channels would correspond to ARTCC sector frequencies. In navigation frequency pairing, enroute H or L class VOR frequencies would be paired with NAS TSD channels and TVOR, ATIS, or ILS frequencies could be paired with appropriate ARTS channels.

2.6 TSD Benefits to the Pilot

At present, pilots construct a mental image of the traffic environment from information received through radio communications, visual scanning for other traffic, knowledge of standard procedures, and previous experience. A pictorial situation display provides this traffic information to the pilot at a glance. The uncertainty and ambiguity associated with mentally synthesizing a time varying traffic situation is largely eliminated. Unlike the information received through present sources, data from a TSD is available whenever a pilot needs it.

Positive and continuous indication is given when adequate separations between aircraft exist. A TSD provides assurance to the pilot when the ATC system is functioning properly. In future years, this will become increasingly important as new procedures are introduced which greatly reduce lateral, longitudinal and vertical separations between aircraft.

Through the advanced cues which a TSD provides, a crew can plan farther ahead and make better decisions. Flap schedules, pressurization regulation, completion of checklists and many other items can be more appropriately timed. A picture of the overall traffic situation can provide an indication of when pilot requests for direct routings, altitude changes, detours etc., can or cannot be approved. If ground or airborne weather radar data is included on the TSD, pilots will be able to monitor weather detours of other aircraft. Cooperation between pilots in a heavy weather area can lead to a better choice of alternate routes for all aircraft involved. Also, by seeing the overall traffic situation, weather deviations can be chosen which will both satisfy weather avoidance criterion and keep disturbance of the traffic flow to a minimum.

Reaction times in an emergency situation can be greatly reduced by a TSD. Response to a "surprise" clearance resulting from an airborne or ground emergency sometimes requires time consuming preparation, especially if aircraft configuration changes are involved. A TSD can take away the surprise in most situations because a pilot can detect the earliest deviations from the normal. The traffic situation can be continuously monitored in parallel with the air traffic controller. By careful observation of the TSD, pilots can be alerted to unusual or potentially threatening situations much sooner than can now be expected. Through this advanced notice pilots can be awaiting an amended clearance and preparations to execute that clearance can be initiated much sooner. A TSD would be particularly useful for monitoring aircraft on parallel ILS approaches. In the event that a nearby aircraft unexpectedly deviated from its intended course, the TSD would provide timely warning that a conflict was developing before the situation became critical. The pilots would have a source of information for evaluating the threat, considering alternative courses of action and accomplishing an evasive maneuver in the event that a clearance which resolved the issue was not forthcoming. If an emergency clearance or collision avoidance instruction was issued by ATC, the pilots would have an indication of the urgency of the situation by being able to see the reason for the clearance.

When certain types of ATC failures occur, such as loss of a radio communications channel during radar vectors, a TSD can offer an added margin of safety or even an avenue of escape by showing potentially conflicting traffic. If the controller's intentions were known, appropriate maneuvering for landing could be continued until a workable frequency was found.

A traffic situation display provides the pilot with a means to cross check the validity of an ATC clearance. Altitudes, routings, headings and speeds can be evaluated in the context of the traffic situation. In cases where many aircraft are being handled, clearances are being transmitted at a high rate and reception is garbled. Messages can be misdirected to aircraft or accepted by incorrect aircraft. Pilots are often the first to discover such inconsistencies. A TSD will better enable pilots to identify inappropriate clearances and it will provide assurance when proper clearances are issued.

Providing data on the surrounding traffic environment will be especially important if dependence on voice communication channels is reduced due to introduction of the digital data link. Radio channels enventually are to be used in a backup mode which will provide little information about clearances to other aircraft. A TSD can restore the pilot's image of the surrounding traffic environment which otherwise will be lost as voice communications are phased out.

A TSD can contribute to increased safety by providing proximity awareness information. Current ATC practices provide traffic advisories to pilots of certain VFR and IFR aircraft on a controller-workload-permitting basis. Range, azimuth, and altitude (when known) are "called" at various warning distances varying from about 8 miles to 1 mile. The amount of warning distance or time given varies with closure speed, anticipated miss distance, assumed target altitude, visibility and many other parameters. Considerable variation of criterion and limits has been observed among controllers within a particular facility and between facilities.

Due to the controller's inability to accurately determine aircraft heading, the azimuth component of a radar traffic advisory is frequently found to be in error. Errors of $\pm 60^{\circ}$ are typical and errors as large as $\pm 120^{\circ}$ sometimes occur. When traffic is heavy, advisories are sometimes given only at very low range values or not at all, particularly if an unidentified target is believed to be at an altitude above or below the subject aircraft.

A TSD provides the pilot with a continuous display of information with predictable quality. Because own aircraft heading data is used to orient the TSD, target azimuth will have better accuracy than can be expected with radar advisories. The progress of an approaching aircraft can be monitored on the TSD until the target is within visual range. The pilot can then concentrate his outside traffic search in the specific area indicated by the TSD.

By monitoring the TSD,pilots can become aware of traffic long before a threat develops. A small path correction which is made while a target is far away may eliminate the need for large corrections or evasive maneuvers.

At present,it is not envisioned that TSD's will take the place of collision avoidance (CAS) or proximity warning (PWI) systems. However, it does appear that TSD's can contribute to their effectiveness. When used with a CAS, a TSD can provide confirmation of maneuver commands. The pilot of an aircraft which receives an instruction for a collision avoidance maneuver will, through knowledge of the evolving traffic situation, be able to see:

1. that a threat actually exists,
2. that the sense and magnitude of the command are correct,
3. if the other aircraft is responding and
4. if the maneuver instruction is likely to cause further conflicts.

TSD's can be used in conjunction with PWI systems to determine and carry out acceptable responses to collision threats.

Subject pilot opinions regarding the effectiveness of a TSD as a proximity awareness device are summarized in Table 2.4.

When operations are being conducted in certain types of instrument weather condition such as "in and out of clouds", near sloping cloud decks, or at night, visual illusions regarding adequacy of separation can occur. A traffic situation display can assist the pilot in combatting these erroneous sensations by removing the element of surprise. By keeping the pilot aware of location, altitude and heading for nearby aircraft, visual illusions and potential threats can be more readily identified.

Table 2.4

Proximity Awareness and Collision Avoidance Survey Results

Percent Response for Each Alternative	Opinion Scale	Pilots rated statements 1 through 4 with the opinion scale shown at the left
93%	Agree	1. A TSD will assist in sighting other aircraft because it will show the pilot where to localize and concentrate his search and when it is necessary to look outside.
7%	Mostly Agree	
	Neutral	
	Mostly Disagree	
	Disagree	
7%	Agree	2. A TSD will direct the pilots attention inside the cockpit to the point that traffic scan will be degraded and possible threats will be missed.
23%	Mostly Agree	
7%	Neutral	
7%	Mostly Disagree	
56%	Disagree	
	Agree	3. A TSD will degrade the pilots search for traffic because of the continuing need to change between near vision focus for the TSD and distant vision focus to spot aircraft.
7%	Mostly Agree	
	Neutral	
	Mostly Disagree	
78%	Disagree	
7%	Agree	4. A TSD will distract pilot attention from other necessary cockpit functions.
7%	Mostly Agree	
7%	Neutral	
7%	Mostly Disagree	
72%	Disagree	

5. As a proximity warning or collision avoidance device a TSD:

Percent Response	Alternative
65%	A. Will enable the pilot to successfully detect, resolve, and avoid most collision threats without a separate collision avoidance system which gives maneuver commands. Misinterpretation of situations and misreaction to threats will be infrequent.
22%	B. Will enable the pilot to successfully detect, resolve, and avoid some threats but misreaction may be a significant problem.
13%	C. Should be used only as a device which supplements collision avoidance system commands by showing the relationship of maneuver commands to traffic situation.

Two additional questions were included in the post-run questionnaire. The first solicited pilot opinion regarding misuse or misreaction to data provided by a TSD and the second considered the overall effect of a TSD on safety. The results are given in Tables 2.5 and 2.6.

2.7 TSD Benefits to ATC

Response time to controller commands can be reduced because awareness of the overall ATC situation can enable a pilot to plan ahead for anticipated maneuvers. Reaction can be more precise and at the proper rate to achieve the controller's intention.

The information transfer process between the controller and pilot can be more efficient when a TSD is available. Controller's instructions can be simplified and abbreviated because a common data base is used. Stipulations of a clearance can be defined relative to the actual ATC traffic constraint, instead of indirectly through navigation fixes such as crossing radials, DME distances or altitudes.

A cockpit traffic situation display can significantly reduce the controller's communications burden by elimination of the need for most situation or traffic advisory messages. This alone can account for a sizable reduction of communications. In a brief study of present operations in the Boston TRACON, it was determined that 34% of the messages initiated by an approach controller observed at random were advisory in nature. The sample was taken over a 30 minute period with high density traffic in bad weather.*

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* Weather:	Ceiling 500' broken, 1000' overcast, visibility 2 miles light rain and fog. Wind 180^{o} at 14 knots
Time:	2000 EDT to 2030 EDT
Controller:	126.5 MHz approach control position
Total No. of messages:	83

Table 2.5

Display Misuse or Abuse Survey Results

Definition: <u>MISUSE OR ABUSE</u>

Unauthorized operations or operation contrary to ATC clearance — Also, operations which violate good operating practices, though being legal.

Examples: Attempting to take unauthorized shortcuts in procedures, disregarding clearances, frequent requesting of special treatment which may unduly increase controller work-load, maneuvering so as to "beat out" other traffic for approach, etc.

Percent Response for Each Alternative	Pilot misuse and abuse of information presented on a TSD:
	1. Will be widespread.
	2. Will occur with sufficient frequency that the overall usefulness of the display function will be in question.
64%	3. Will occasionally occur but will not significantly detract from the usefulness of the display function.
36%	4. Will rarely occur.

Table 2.6

Safety Survey Results

Percent Response for Each Alternative	Evaluation of the overall contribution of this display to flight safety is:
75%	1. The display provides a great improvement in safety.
25%	2. The display provides a slight improvement in safety
	3. The display has a neutral effect on safety-improvements in some areas are balanced by adverse effects in other areas.
	4. The display contributes to a slight reduction in safety.
	5. The display create hazards through potential distraction, misreaction, and misuse and greatly decreases safety.

Messages of an advisory nature are considered to be those which are non-essential for control purposes but are related to keeping the pilots informed of the overall situation. Examples of typical advisory messages are:

> "American 11 you are number three for approach behind an Eastern DC9, 11 o'clock 6 miles, just passing the Lynnfield beacon".

> "Allegheny 862 I'll be taking you through the localizer for additional spacing, expect a speed reduction in 5 miles".

If the aircraft being controlled during this sample period were equipped with TSD's, most of the advisory messages (34% of the total number of transmitted messages) could have been eliminated.

Another area where a TSD can make a significant contribution is in providing increased flexibility for the ATC system. Cases arise where controllers must exercise judgements regarding pilot and aircraft performance capability. The examples which occur most frequently are controller estimation of climb, descent and speed capability. Often unduly restrictive procedures and safety margins must be employed to accommodate a wide range of aircraft performance and pilot responses. However, if pilots are aware of the controller's objective, compliance with a clearance can be accomplished in a specific manner favorable to ATC, thus freeing airspace which would be protected for a range of responses. With a TSD, pilots can cooperate with controllers in this way much more frequently than now possible because of an increased awareness of overall traffic flow and control objectives. Timely suggestions and increased assistance in achieving specific aircraft response can contribute to greater efficiency in both terminal and enroute operations.

The effectiveness of certain procedures currently employed in terminal area operations in visual conditions can be increased through use of a TSD. A prime example of this is the potential for improvements to visual approach procedures for IFR aircraft. A TSD can provide the pilot the means to positively identify traffic of interest such as an aircraft which is to be followed. Speed and path changes can be observed much sooner than now possible by visual estimation. Range and range rate can be determined more accurately and at greater separations. A TSD would be particularly helpful for flying in haze conditions, at night, towards a sun low on the horizon, or in other reduced visibility conditions. As a result, more precise maneuvering can be expected and clearance for visual approach may be granted sooner in the approach profile and in a wider variety of weather conditions. The significance of improved or extended visual approach procedures is very great because flow capacities are generally much higher when these procedures can be employed. Pilot opinion of TSD merit in a visual approach situation is given in Table 2.7.

Table 2.7

Pilot Opinion of TSD Merit in Visual Approach Situations

Percentage response to visual approach statement	Response	Statement
79%	Agree	A TSD will enable pilots to attain and maintain more accurate spacing during visual approaches.
7%	Mostly Agree	
7%	Neutral	
	Mostly Disagree	
7%	Disagree	

CHAPTER III

THE EXPERIMENTAL PROGRAM

3.1 Description of the Simulation Facility

The essential elements of the real world that were to be modelled were the cockpit environment, aircraft characteristics, and ATC situations. Since TSD's would most likely be introduced in transport category aircraft, initial simulation was directed towards this application.

A fixed base research simulator using CRT's to generate both flight instruments and the TSD served as the basic component of the simulation. Its aircraft dynamics were similar to a Boeing 707-123B. The cockpit, computer, associated hardware, and data recording equipment are shown in schematic form in Figure 3.1.

A fixed base simulation was used in initial experiments because time constants associated with the tasks which would be performed were long compared to motion cues experienced in flight. Turbulence effects, which may contribute to decreased task performance, were estimated by subject pilots in post-run questionnaires. Exterior and interior views of the cockpit are shown in Figures 3.2 and 3.3.

The captain's flight group instruments were a CRT generated representation of the Collins FD-109 integrated flight system. This system is typical of instrument systems used in current generation transport aircraft.

Because of the high percentage of time in which full or partial autopilot components are used in air carrier work, initial tests were conducted with "control wheel steering" (CWS). This flight control system provides aircraft attitude stabilization while the pilot uses the control wheel in much the same manner as when manually flying the aircraft.

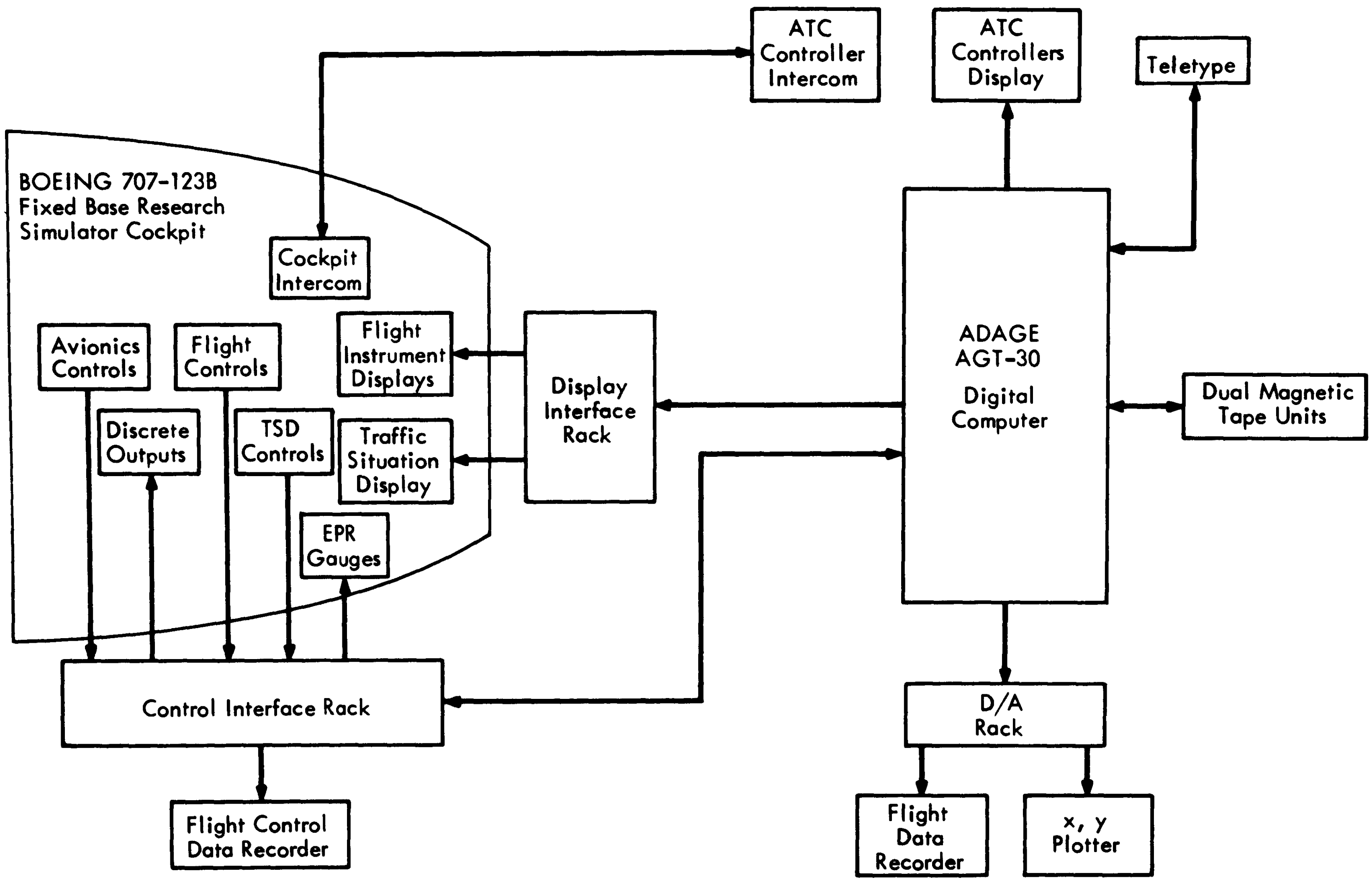


Figure 3.1 Simulation Facility Block Diagram

Fig. 3.2 Cockpit Simulator

Fig. 3.3 Interior View of Cockpit

Similar CWS systems are available on Boeing 737, Douglas DC-10 and several other types of aircraft.

All approaches were flown using raw localizer and glide slope data. Coupled approaches and steering commands are to be included in later experimentation.

Co-pilots were provided as part of the experimental setup. ATC clearances and communications were simulated by the experimentor for all cases except the ones which tested controller performance. In these experiments, line ATC controllers were used.

In post-run questionnaires, subjects were asked to rate the acceptability of the aircraft simulation. Subject responses are given in Table 3.1.

Table 3.1

Simulator Evaluations

The aircraft simulation:

33%	1. Realistically models the performance and response of a transport category jet aircraft in the essential-parameters which bear on the tasks of the experimental program.
67%	2. Has minor deficiences, but for the purposes of this set of experiments, it adequately models a transport category jet aircraft. (The deficiencies of the simulation are noticed by the pilot but they will most likely not affect the validity of the data.)
	3. Has notable deficiencies which may affect the validity of some data.
	4. Has serious deficiencies which will introduce major errors in the data.

The Adage AGT-30 digital computer served as the central element of the simulation facility. The Adage computer has a 16K core memory with a 2 microsecond cycle time. In real time, the computer calculated flight dynamics, recorded and processed data, generated target aircraft profiles and maintained the following three displays:

1. flight instruments,
2. traffic situation display, and
3. air traffic controller ARTS III display.

In addition, the computer provided analog outputs for data recorders.

A software summary which lists major programs, subroutines and describes their function is given in Table 3.2.

Table 3.2

SOFTWARE			
PROGRAM NAME	SUBROUTINES	DESCRIPTION	DISPLAY
ACSIM	(AERO, SICOS, DIRCS)	AIRCRAFT SIMULATION	
	(FNSW)	READ FUNCTION SWITCH BOX	
	(RDISC)	READ DISCRETE INPUTS	
	(VCD 1)	READ ANALOG OUTPUTS	
	(MKLTS)	CONTROL MARKER LIGHTS	
FINST	(ICAL 1, ICAL 2)	FLIGHT INSTRUMENT CALCULATIONS	FLIGHT INSTRUMENTS
MMAP	(SSFLS, BPARL)	MAP DISPLAY CALCULATIONS	MAP
TRFFL	(TMOVE)	TRAFFIC DISPLAY AND MOVEMENT CALCULATIONS	TRAFFIC
VALUP	(VALUP)	REAL TIME DATA PROCESSING	
HOMR	(HOMR)	HEAD ORIENTATION MONITOR (OPTIONAL)	

3.2 ATC Environment

ATC situations were based on the Boston terminal area. An area radio navigation chart depicting the details of this area is presented in Figure 3.4.

Flight track data was collected and target profiles based on actual approach tracks from Millis, Whitman and Acton (three of the primary Boston holding fixes) to the runway 4R ILS approach were constructed and programmed. Clearances and other communications were reconstructed from voice tapes of controller-pilot radio transmissions.

A wind model based on typical Boston area surface and winds aloft reports was included in the simulation as a disturbance. Both direction and velocity of wind varied with altitude.

3.3 Description of Test Cases

A summary of the test cases is given in Table 3.3. A fuller description of the test cases can be found in Chapter IV.

The nominal target aircraft profiles are shown in Figure 3.5.

In addition to the above cases, several radar vector comparison tests were run using rated ATC controllers and a simulated ARTS III display. For these tests, the subject aircraft was flown without the traffic situation display.

3.4 Subject Pilots

Subjects chosen for the experiments were all rated pilots. Primary emphasis was on using subjects with either large aircraft (gross weight over 12, 500 lbs) or high performance jet aircraft experience. For initial tests

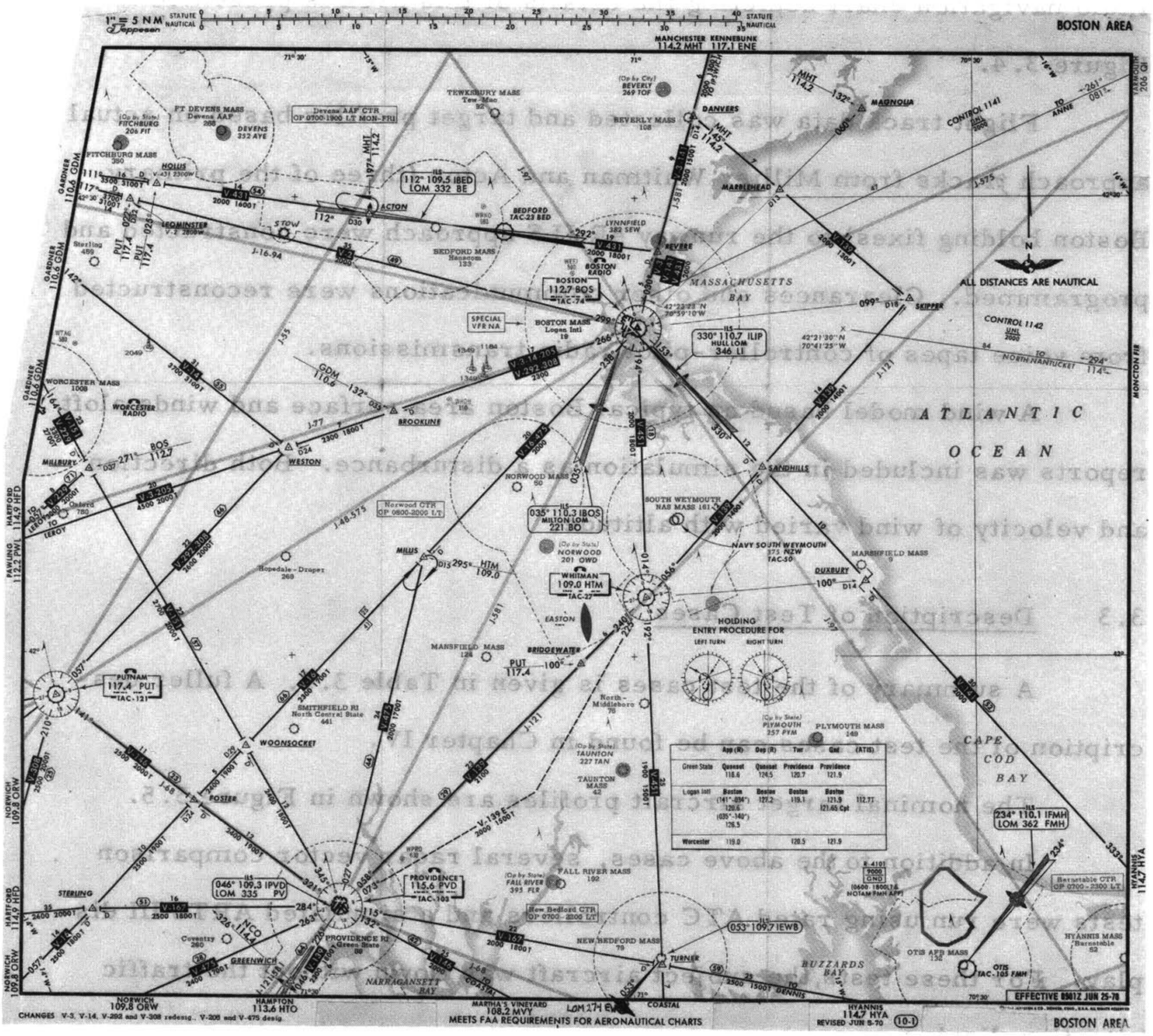


Fig. 3.4 Radio Navigation Chart for the Boston Area

Table 3.3 Test Case Summary

CASE SUMMARY							
CASE	**DESCRIPTION**	**TASK**	**INITIAL CONDITIONS AND COMMUNICATIONS**	**TARGET PROFILE**	**MAP**	**DEGREES OF FREEDOM**	**NOTES**
1	BASIC TEST ON A CONSTANT COURSE	ACQUIRE AND TRACK BEHIND TARGET AIRCRAFT AT 4 nm SPACING	SUBJECT AIRCRAFT STARTS 7 nm BEHIND TARGET AIRCRAFT NO COMMUNICATIONS	TARGET FOLLOWS AIRWAY AT CONSTANT ALTITUDE AND AIRSPEED	BASIC AND AIRWAY	SPEED CONTROL	DEFINES LIMITS OF STEADY STATE TRACKING ACCURACIES MEASURES ARE: TIME TO ACQUIRE, OVERSHOOT, MEAN AND STANDARD DEVIATION OF SPACING
2	BASIC TEST FOR CURVED COURSE	ACQUIRE AND TRACK BEHIND TARGET AIRCRAFT AT 6 nm SPACING	SUBJECT STARTS 8 nm BEHIND TARGET AIRCRAFT, ON AIRWAY TO HOLDING FIX (ACTON) NO COMMUNICATIONS	TARGET FLIES AIRWAY TO HOLDING FIX, TURNS RIGHT 60°, MAINTAINS SPEED FOR 6 MINUTES THEN DECELERATES	BASIC	SPEED AND PATH CONTROL	CASES 2 AND 3 COMPARE THE EFFECTIVENESS OF SPEED AND PATH CONTROL VS. SPEED CONTROL ALONE. MEASURES ARE: TIME TO ACQUIRE, INITIAL OVERSHOOT, LIMITS OF MANEUVERING AIRSPACE
3	BASIC TEST FOR CURVED COURSE	ACQUIRE AND TRACK BEHIND TARGET AIRCRAFT AT 6 nm SPACING	SUBJECT STARTS 8 nm BEHIND TARGET AIRCRAFT, ON AIRWAY TO HOLDING FIX, (ACTON) NO COMMUNICATIONS	TARGET FLIES AIRWAY TO HOLDING FIX, TURNS RIGHT 60°, MAINTAINS SPEED FOR 6 MINUTES THEN DECELERATES	BASIC AND TRANSITION ROUTES	SPEED CONTROL ONLY	
4	ATC SITUATION RELATED SPACING TEST	ACQUIRE AND TRACK BEHIND TARGET AIRCRAFT THRU ENTIRE APPROACH PROFILE - AS CLEARED	AIRCRAFT POSITIONED AS IN CASES 2 AND 3 FULL COMMUNICATIONS INCLUDING RADAR VECTORS TO TARGET AIRCRAFT	FLIES COMPLEX PROFILE FROM HOLDING PATTERN TO TOUCHDOWN - BASED ON TRACKS OF ACTUAL AIRCRAFT IN BOSTON TERMINAL AREA	BASIC	SPEED AND PATH CONTROL	CASE 4 MODELS PRESENT ATC TERMINAL AREA SITUATION WITH THE ADDITION OF TSD's IN SELECTED AIRCRAFT MEASURES ARE: DELIVERY ACCURACY AT OUTER MARKER, PILOT WORKLOAD, COMMUNICATIONS VOLUME AND LIMITS OF MANEUVERING AIRSPACE
5	ATC SITUATION RELATED SPACING TEST	ACQUIRE AND TRACK BEHIND TARGET AIRCRAFT THRU ENTIRE APPROACH PROFILE - AS CLEARED USING STARS AND TRANSITIONS	AIRCRAFT POSITIONED AS IN CASES 2 AND 3 FULL COMMUNICATIONS	FLIES COMPLEX PROFILE FROM HOLDING PATTERN TO TOUCHDOWN - BASED ON TRACKS OF ACTUAL AIRCRAFT IN BOSTON TERMINAL AREA	BASIC AND TRANSITION ROUTES	SPEED AND PATH CONTROL	CASE 5 MODELS ADVANCED STAGES OF ARTS III TERMINAL AREA WHERE NEW PROCEDURES TAKING ADVANTAGE OF AREA NAVIGATION COULD BE USED MEASURES ARE SAME AS THOSE USED IN CASE 4
6	ATC SITUATION RELATED MERGING TEST	MERGE BEHIND AND FOLLOW TARGET AIRCRAFT FOR APPROACH AT 4 nm SPACING	SUBJECT STARTS ON AIRWAY, APPROACHING HOLDING FIX (MILLIS) TARGET STARTS AT HOLDING FIX (WHITMAN) FULL COMMUNICATIONS	TARGET AIRCRAFT FLIES COMPLEX PROFILE TO INTERCEPT ILS, THEN FLIES ILS TO TOUCHDOWN	BASIC	SPEED AND PATH CONTROL	CASE 6 TESTS MERGING, WITH ATC SITUATION AND MEASURES AS IN CASE 4
7	INSTRUMENT CONDITION ANALOG OF VISUAL TRAFFIC PATTERN	ACQUIRE AND FOLLOW TARGET AIRCRAFT FOR FINAL APPROACH AT 3 nm SPACING	SUBJECT AIRCRAFT STARTS ON 3 nm DOWNWIND LEG ABEAM AIRPORT TARGET STARTS ON FINAL APPROACH, 8 nm FROM THE OUTER MARKER	TARGET FLIES ILS TO TOUCHDOWN, DECELERATING TO FINAL APPROACH SPEED .5 nm BEFORE REACHING OUTER MARKER	BASIC	SPEED AND PATH CONTROL	CASE 7 DEMONSTRATES SPACING CONTROL USING TROMBONE PATTERN (ANALOG OF VISUAL TRAFFIC PATTERN)) MEASURES AS IN CASE 4
8	FINAL APPROACH AND LANDING, SPACING TEST	CONSISTENT WITH SAFETY AND WITH LOW PROBABILITY OF GO-AROUND, ACHIEVE MINIMUM SPACING BEHIND TARGET AIRCRAFT ON FINAL APPROACH	SUBJECT STARTS 4 nm BEHIND TARGET. BOTH AIRCRAFT ARE ESTABLISHED ON LOCALIZER	TARGET MAINTAINS 160KTS ON LOCALIZER UNTIL 2 nm BEFORE OUTER MARKER TARGET THEN DECELERATES TO FINAL APPROACH SPEED FOR ILS	BASIC	SPEED CONTROL PATH CONSTRAINED TO ILS	GO AROUND DEFINED AS SUBJECT AIRCRAFT ARRIVING AT CAT II DECISION HEIGHT BEFORE TARGET AIRCRAFT CLEARS RUNWAY CASE 8 PROBES PSYCHOLOGICAL EFFECTS OF CLOSE SPACINGS ON LANDING APPROACH
9	POSITION COMMAND DATA TEST-BASIC	ACQUIRE AND TRACK GROUND-GENERATED, TSD-DISPLAYED POSITION COMMAND DATA FOR FINAL APPROACH	SUBJECT STARTS AT HOLDING FIX (MILLIS) COMMAND BUG STARTS ON EXTENDED LOCALIZER CENTERLINE, 15 nm FROM THE OUTER MARKER	COMMAND BUG FLIES LOCALIZER COURSE TO TOUCHDOWN	BASIC	SPEED AND PATH CONTROL FOR ACQUISITION PHASE	CASES 9 AND 10 INVESTIGATE USE OF PICTORIAL DISPLAYS TO PRESENT POSITION COMMAND DATA MEASURES ARE: STANDARD ERRORS, WORKLOAD, DELIVERY ACCURACY AT OUTER MARKER AND LIMITS OF MANEUVERING AIRSPACE
10	POSITION COMMAND DATA TEST - COMPLEX	ACQUIRE AND TRACK GROUND-GENERATED, TSD-DISPLAYED POSITION COMMAND DATA FOR ENTIRE APPROACH - FROM HOLDING FIX TO TOUCHDOWN	SUBJECT STARTS AT HOLDING FIX (MILLIS) COMMAND BUG STARTS ON INBOUND LEG OF HOLDING PATTERN	COMMAND BUG MAKES ONE CIRCUIT OF HOLDING PATTERN, THEN FOLLOWS COMPLEX PROFILE TO TOUCHDOWN	BASIC AND TRANSITION ROUTES AND HOLDING PATTERN	SPEED AND PATH CONTROL FOR ACQUISITION PHASE	

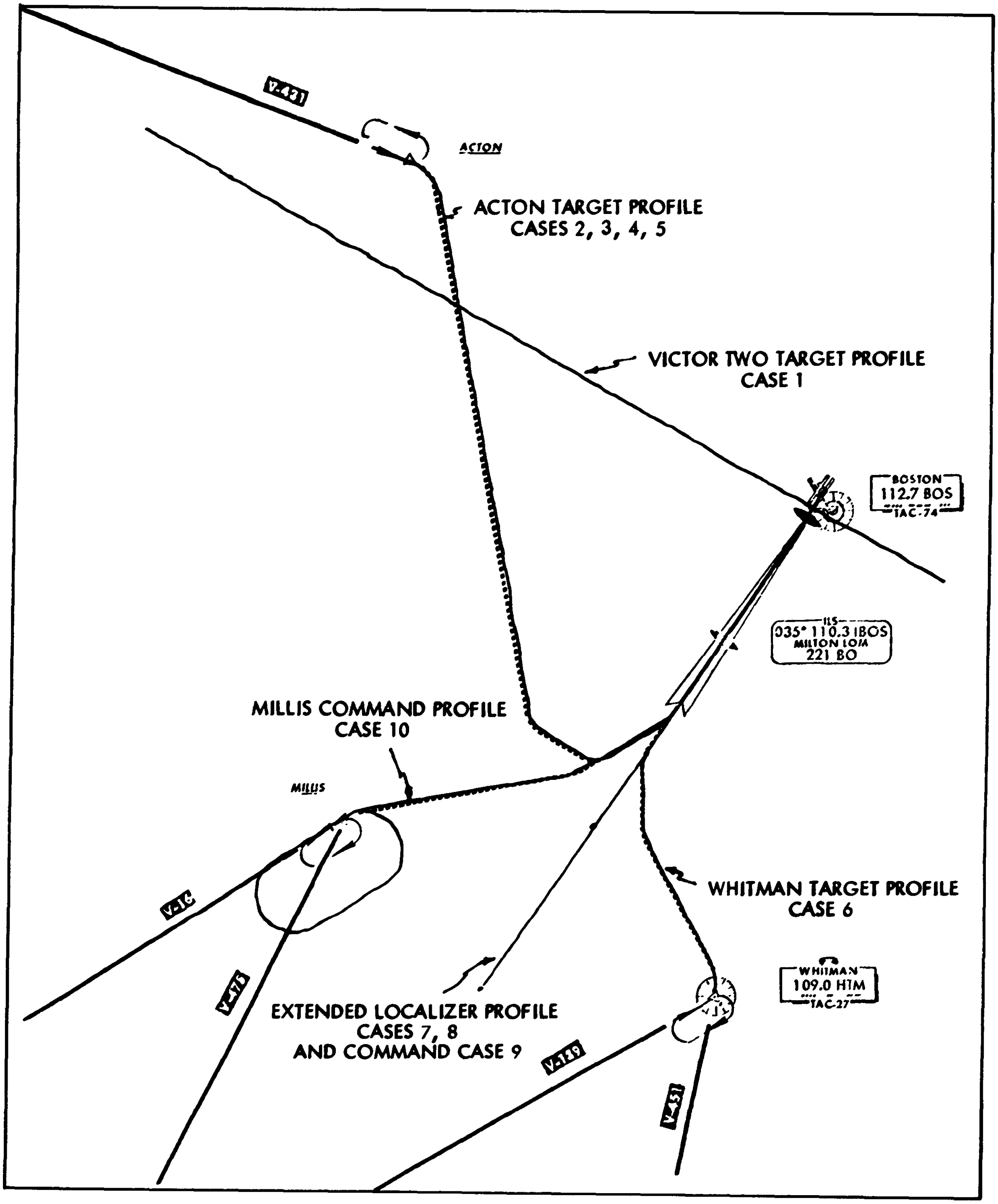


Figure 3.5 Target and Command Bug Profiles

six airline pilots, six military pilots, and two general aviation pilots were chosen as subjects. All subjects had previous experience in fixed base simulators. It was hoped that military pilots could apply previous experience of formation flight, rendevous techniques, and airborne radar intercepts to performance of the tasks. It was felt that this experience would lead to a level of performance indicative of that attainable by other pilots after equivalent training with a TSD. A summary of subject pilot flight experience is given in Table 3.4.

3.5 Training

Subject training was accomplished in three phases:

1. briefing,
2. aircraft transition training, and
3. task training.

The introduction to the training session was a general briefing regarding the simulation facility and the experimental program. This was followed by instruction in aircraft characteristics, flight instrument system, flight control system, avionics, and the traffic situation display controls. Directions were then given for use of the questionnaires which were to be completed after each case. Finally, enroute radio charts, approach plates, SID's and STAR's appropriate to the experiments were reviewed.

Each subject was given approximately three hours of flight simulator training. The first hour was directed toward aircraft familiarization. This phase consisted of takeoff, SID, airwork, aircraft limitations (flap schedules, ..., etc.) and approaches. The remaining two hours emphasized use of the TSD and task training. Subjects were trained until the standard tolerances

Table 3.4 Subject Pilot Flight Experience Summary

SUBJECT NUMBER	TOTAL FLIGHT HOURS	ACTUAL OR SIMULATED HOURS OF INSTRUMENT FLIGHT	APPROXIMATE NUMBER OF HOURS IN FLIGHT SIMULATORS	LARGE MULTIENGINE JET AIRCRAFT (B707, B727, DC9, ...)	OTHER JET AIRCRAFT (T33, T38, F4, ...)	MULTIENGINE RECIP OR TURBOPROP	SINGLE OR MULTIENGINE LIGHT AIRCRAFT	RATINGS	NOTES
1	560	100	3		✓		✓	COMML SMEL, INST, CFI-A-1	
2	1,650	200	200				✓	COMML SMEL, SES, INST, CFI-A-1, HELICOPTER	RESEARCH PILOT EXPERIENCE
3	24,000	2,800	78	✓		✓	✓	ATR, COMML SEL, DC3, M202/404 CV340/440/540/580, DC9, CFI-A-1	CURRENTLY DC9 CAPTAIN FOR SCHEDULED AIRLINE
4	1,800	700	300		✓				SENIOR PILOT USAF
5	1,300	300	100		✓		✓	COMML, INST	USAF PILOT
6	1,100	350	150		✓	✓	✓		RCAF TRANSPORT CAPTAIN
7	15,500	3,000	40	✓		✓	✓	ATR, COMML SEL, M404, L49, DC9, CFI-A-1	CURRENTLY DC9 CAPTAIN FOR SCHEDULED AIRLINE
8	1,200	200	50		✓				USN PILOT
9	27,000	2,700	14	✓		✓	✓	ATR, COMML SELS, DC3, M202/404 CV/340/440/540/580, DC9, B727	CURRENTLY B727 CAPTAIN FOR SCHEDULED AIRLINE
10	2,800	400	50		✓		✓	COMML SMEL, INST, CFI-A-1	USN PILOT
11	2,800	400	200			✓	✓	COMML SMEL, INST, FLIGHT ENGINEER TURBOPROP	CURRENTLY L188 ELECTRA F/O FOR SCHEDULED AIRLINE
12	9,700	1,000	300	✓		✓	✓	ATR, B707, C124	CURRENTLY B707 CAPTAIN FOR SCHEDULED AIRLINE - SIMULATOR INSTRUCTOR FOR C124 - USAFR
13	5,000	1,000	350			✓		COMML SMEL, INST, TB25	USAF SENIOR PILOT
14	4,500	200	20	✓	✓	✓	✓	COMML SMEL, INST, CFI-A-1	CURRENTLY B727, F/O FOR SCHEDULED AIRLINE

of instrument flight could be met.

$\pm$100 feet altitude error

+10, -0 knots airspeed error on approach

$\pm$ 5^{o} heading error

$\pm$1 Dot on glide slope and localizer during ILS approach

Since hydraulic, electrical, pressurization, fuel and other systems were not emphasized in the training, more time could be spent on learning the aircraft handling qualities. The resultant pilot learning effects and levels of performance were comparable to those experienced during actual aircraft transition programs.

For task training, learning effects were noted by comparing data sets taken early in training with those taken near the end of the training session and by comparing training performance with final data runs of similar cases. Generally, task learning was very rapid. On similar cases, it is estimated that diminishing returns on learning occurs by the third trial. After several hours of training, subjects can handle most new situations. By the time the data runs were completed (7 to 9 hours), subjects expressed the opinion that new situations could be handled easily. Analysis of performance data (spacing accuracies) and workload data (frequency of control reversals and questionnaires) confirmed these results.

Contrary to expectations, no significant differences in learning between military pilots (with formation, radar intercept, etc. experience) and line pilots was observed. It is believed that VFR flying experience (such as operating in a traffic pattern and following aircraft on visual approaches) in both pilot groups was easily applied to the tasks using the TSD and this factor was of much greater significance than the particular military experience mentioned above.

Subjects generally felt that once basic tasks were mastered, little effort would be required to maintain proficiency. The only check on proficiency which was made in the test program compared subject performance in a data session to performance in a training session two weeks earlier. No significant differences were noted.

To minimize the effects of learning on data runs, the test cases summarized in Table 3.3 were flown in random order. The run procedure which was used is presented in Table 3.5.

3.6 Data Acquisition and Processing

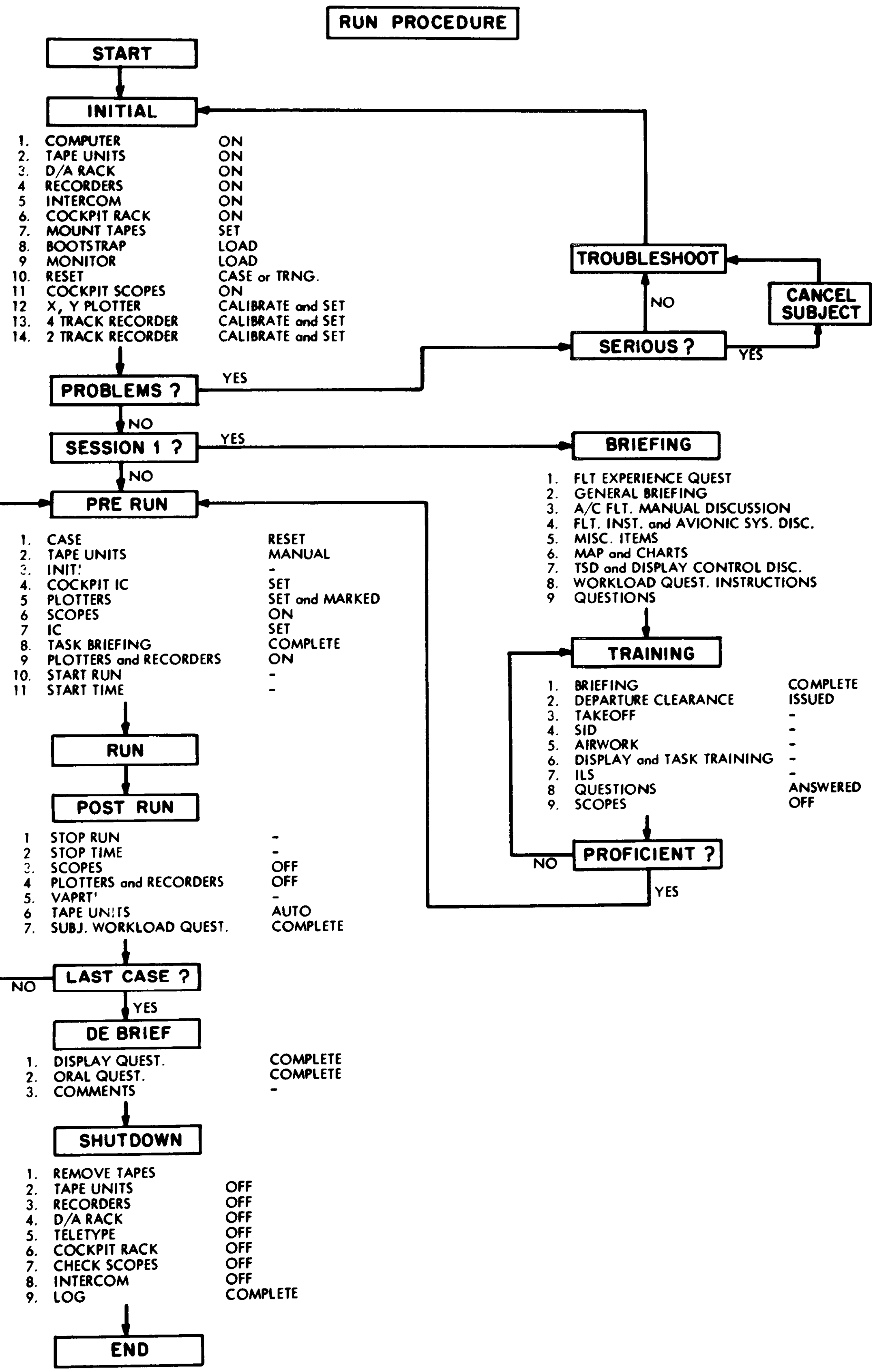
During each run, ground tracks of the subject aircraft were recorded on an X, Y plotter. Other data was recorded on strip charts as follows:

1. $R_{st}(t)$ Range between subject and target aircraft,
2. $\Delta V_{g/s}(t)$ Velocity difference (based on ground speed) between subject and target aircraft,
3. $V_{IAS}(t)$ Indicated airspeed of subject aircraft,
4. EPR(t) Engine pressure ratio (measure of thrust) of subject aircraft,
5. $\Theta_{CMD}(t)$ Control wheel steering pitch command,
6. $\phi_{CMD}(t)$ Control wheel steering roll command.

A timing track on the recorder was alternately used as an event marker for recording the time spent by the subject pilot looking at the TSD.

$\Theta_{CMD}(t)$, $\phi_{CMD}(t)$, and EPR(t) records were used as measures of pilot physical workload. Amplitude and frequency of control application was analyzed and the results were correlated with the responses on the workload questionnaire which the subject pilots answered after each case. $V_{IAS}(t)$ was an indicator of pilot technique for achieving proper separation

Table 3.5 Run Procedure



in the test cases. $\Delta V_{g/s}(t)$ and $R_{st}(t)$ were measures of task performance.

In addition, real time parallel processing of data was accomplished by the Adage computer. Mean spacings for designated approach phases, standard deviations, times to acquire a given spacing, and delivery error at the outer marker were computed during the runs. Teletype printout of the results was available immediately following completion of a test run.

CHAPTER IV

TEST RESULTS AND DISCUSSION

4.1 Basic Tracking Tests

Cases 1 through 3 investigate the basic tracking capability of an aircraft-pilot-TSD system in straight and turning flight.

A. Case 1 examined the piloting technique employed when decreasing separation while on a constant courses and it defined the limits of spacing accuracy which could be expected after steady state is established. Pilots of subject aircraft were instructed to close spacing from 7 nm. to 4 nm. behind a target aircraft which maintained a constant course in level flight at 5000' and 160 KTS indicated airspeed. Results of Case 1 are shown in Table 4.1.

The results outlined in Table 4.1 indicate that the limit of steady state tracking performance of the system tested in this simulation is better than ±.1 nautical mile (best estimate of the standard deviation of the population, taken over a 5 minute sample, is .078 nm.). However, biases on the order of +.10 nm. and .12 nm. were experienced due to pilots' willingness to accept small errors as being within a reasonable conformance limit. Deceleration rates experienced during this case are generally consistent with those used in normal operations. Range overshoot occurred in about 50% of the cases, but all instances were quickly and smoothly corrected.

Maximum overshoot experienced in case 1 was .4 nm. No tendency to oscillate about the command range was noticed.

The best procedure for making range adjustments appeared to be:

1. Establish target and subject status and relative velocity from observation of the TSD range and ground speeds.

Table 4.1

Case 1 Results

Initial Spacing = 7.00 nm.

Desired Spacing = 4.00 nm.

Subject #	Mean Steady State Spacing (nm.)	Standard Deviation (nm.)	T_{acq}^{*} (sec)	Initial Spacing Overshoot	Maximum deceleration rate (KTS/sec)
1	4.10	.08	142	.4	1.3
2	4.00	.08	162	none	2.0
3	4.03	.07	164	.10	2.6
4	4.00	.06	194	none	1.33
5	4.00	.05	192	none	1.33
6	4.04	.08	178	.10	1.0
7	3.88	.09	149	.25	2.0
8	3.99	.09	189	.30	2.0
9	4.08	.05	175	none	2.0
	Maximum Positive bias = +.1nm. Maximum negative bias = -.12 nm.	Best estimate of the standard deviation of the population σ = .078nm.			

* T_{acq} = time to acquire — defined as the time to close to a distance equal to 1.1 times desired spacing.

2. Determine the desired relative closure velocity based on range error, closure time, aircraft and configuration limitations, ATC limitations and passenger comfort.

3. Determine a reference IAS which will provide the necessary closure rate.

4. Adjust power and configuration to attain and maintain the reference IAS.

5. Crosscheck TSD range and $\Delta V_{g/s}$ to evaluate the effectiveness of the selected closure rate.

It was generally found that using appropriate velocity increments with IAS as a primary reference provided smoother and more accurate control than could be accomplished by using TSD ground speed as a direct basis for making power or configuration changes.

Subjects also found that due to aircraft limitations, configuration restrictions, and limits of good operating practices it was much harder to increase spacing than to close spacing. Case 1 workload questionnaire results are shown in Table 4.2 Ratings of "improved" reflected the subject's consideration of overall communications, planning, and conformance to repeated vectors and speed changes which would have been necessary to accomplish the task if a TSD were not available to the pilot.

B. Case 2 and 3 considered spacing performance over a simple curved course and during deceleration. The subject aircraft was required to close spacing from 8 nm. to 6 nm. using speed and path control in case 2 and speed control alone in case 3. The paths followed in cases 2 and 3 represent typical turning profiles which are experienced in terminal area maneuvering. The target aircraft in both cases proceeded direct from initial conditions to ACTON, turned right and maintained a 170^{o} ground track at constant

Table 4.2

Response of Subject Pilots to Workload Questionnaire - Case 1	
Choice of Alternatives by Percentage	The phrase which best describes the overall mental and physical workload of flying the aircraft through the required task is:
0 %	A. Unacceptable: Workload is unacceptably high for routine operations — concentrated pilot attention to the exclusion of other essential tasks is required.
0 %	B. Tolerable: Workload is high but tolerable — a considerable amount of pilot attention is focused on the task, however, all essential cockpit functions and most secondary cockpit functions can be completed on schedule in normal operations. Undersirable distractions from the performance of other cockpit tasks are frequent.
60 %	C. Statisfactory: The overall mental and physical workload experienced during this task is not significantly different than that expected in a routine cockpit environment.
40 %	D. Improved: There is a decrease in overall pilot workload from that usually experienced in this phase of flight.

speed and altitude. After 6 minutes, the target aircraft decelerated from 200 knots to 160 knots as shown in Figure 4.1.

Results of case 2 are given in Table 4.3 and Figure 4.2 and case 3 in Table 4.4 and Figure 4.3.

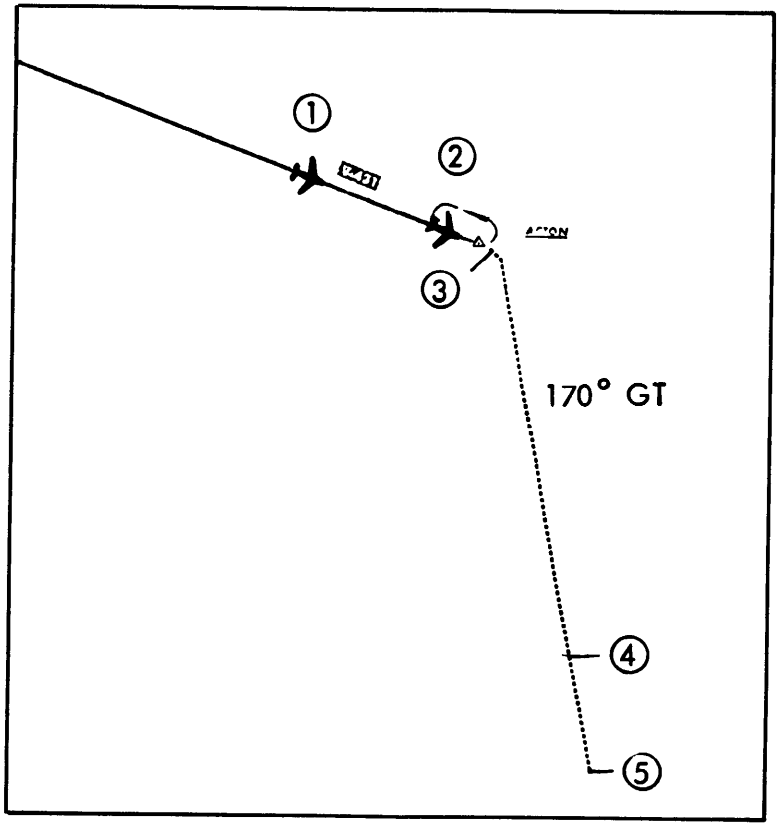
The relative effectiveness of speed control alone (case 3) versus speed and path control (case 2) in this situation can be seen by comparing the time to acquire and maneuvering airspace. Case 3 mean times to acquire are 57% longer than the times recorded in case 2. However, maneuvering airspace used in case 3 is much less than required in case 2, as can be seen by comparing Figures 4.2 and 4.3.

Tracking performance during deceleration was considered in the last phases of cases 2 and 3. Subject pilots were asked to maintain 6 nm. separation behind the target aircraft which accomplished a 40 knot speed reduction at 1 knot/sec. No information regarding the target aircraft's expected profile was given to the subject pilot. In order to maintain the proper spacing, the TSD was used to detect initiation of the speed reduction, determine an approximate deceleration rate and establish a revised steady state speed. Mean spacing of all subjects during the deceleration task was 5.90 nm. Average initial overshoot (mainly due to detection delay) was less than .2 nm.

4.2 ATC Procedural Tests

An important class of benefits of a TSD is the increased efficiency and capacity resulting from modification of existing procedures and implementation of new procedures.

Pilots currently are passive participants in ATC control. With few exceptions, clearances are executed by applying standard responses and



1. Subject aircraft initial conditions
   6000'
   200 knots IAS
   111° heading

2. Target aircraft initial conditions
   6000'
   200 knots G/S
   111° ground track (GT)

3. Target aircraft turns to achieve a 170° GT using 25° bank

4. Target aircraft decelerates at 1 knot/sec to 160 knots G/S

5. End of run

Figure 4.1 Case 2 and 3 Target Profiles

Table 4.3

Case 2 Results

Initial Spacing = 8 nm.
Desired Spacing = 6 nm.

Acquisition

T_{acq} — mean 147.3 sec
— maximum 349.0 sec
— minimum 88.0 sec

Steady State Spacing (Command spacing = 6 nm.)

Maximum positive bias + .16 nm.
Maximum negative bias - .19 nm.

Best estimate of the standard deviation of the population .068 nm.

Deceleration Phase

Grand mean spacing during deceleration 5.94 nm.
Maximum negative spacing bias = -.16 nm.

Response of Subject Pilots to Workload Questionnaire - Case 2

Choice of Alternatives by Percentage	The phrase which best describes the overall mental and physical workload of flying the aircraft through the required task is:
0 %	A. Unacceptable: Workload is unacceptably high for routine operations — concentrated pilot attention to the exclusion of other essential tasks is required.
0 %	B. Tolerable: Workload is high but tolerable — a considerable amount of pilot attention is focused on the task, however, all essential cockpit functions and most secondary cockpit functions can be completed on schedule in normal operations. Undesirable distractions from the performance of other cockpit tasks are frequent.
40 %	C. Satisfactory: The overall mental and physical workload experienced during this task is not significantly different than that expected in a routine cockpit environment.
60 %	D. Improved: There is a decrease in overall pilot workload from that usually experienced in this phase of flight.

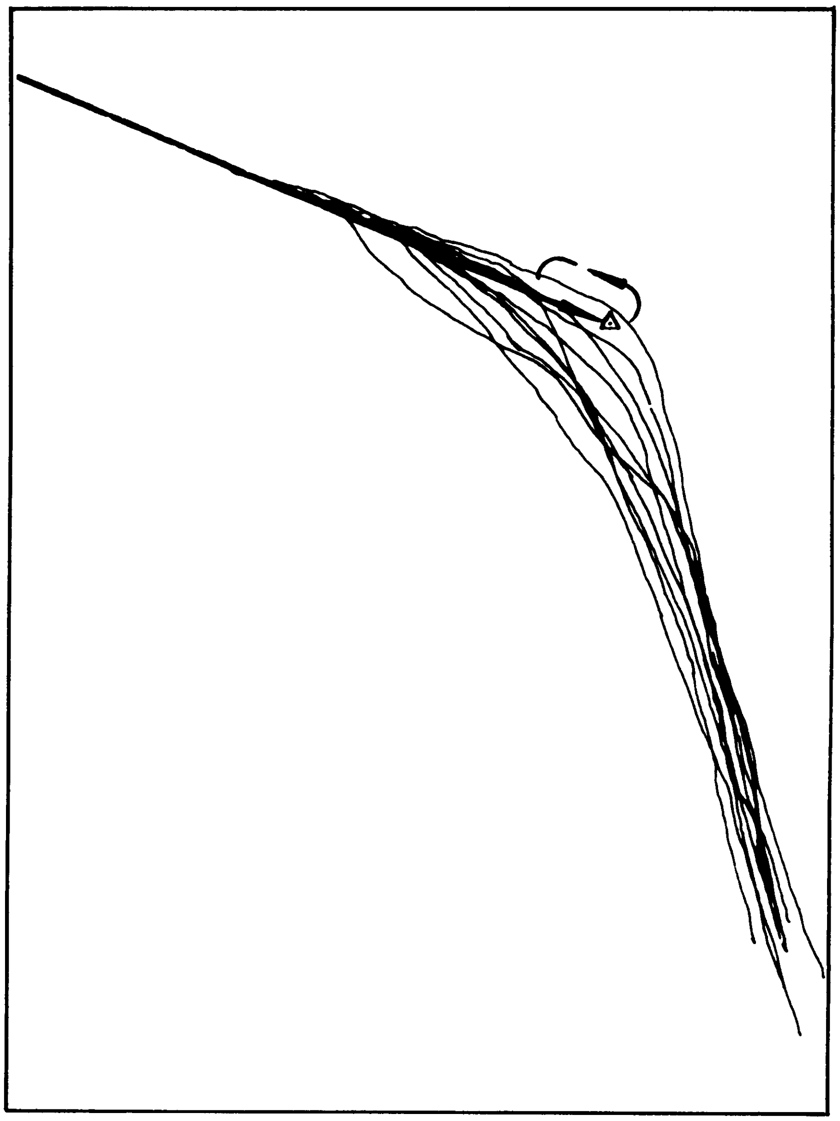


Figure 4.2 Case 2 Track Plots

Table 4.4

Case 3 Results

Initial Spacing = 8 nm.
Desired Spacing = 6 nm.

Acquisition

T_{acq} — mean 232.1 sec
— maximum 387.0 sec
— minimum 98.0 sec

Steady State Spacing (Command spacing = 6 nm.)

maximum positive bias +.05 nm.
maximum negative bias -.09 nm.

Best estimate of the standard deviation of the population .083 nm.

Deceleration Phase

Grand mean spacing during deceleration = 5.90 nm.
maximum negative spacing bias = -.19 nm.

Response of Subject Pilots to Workload Questionnaire - Case 3

Choice of alternatives by percentage	The phrase which best describes the overall mental and physical workload of flying the aircraft through the required task is:
0 %	A. Unacceptable: Workload is unacceptably high for routine operations — concentrated pilot attention to the exclusion of other essential tasks is required.
0 %	B. Tolerable: Workload is high but tolerable — a considerable amount of pilot attention is focused on the task, however, all essential cockpit functions and most secondary cockpit functions can be completed on schedule in normal operations. Undesirable distractions from the performance of other cockpit tasks are frequent.
60 %	C. Satisfactory: The overall mental and physical workload experienced during this task is not significantly different than that expected in a routine cockpit environment.
40 %	D. Improved: There is a decrease in overall pilot workload from that usually experienced in this phase of flight.

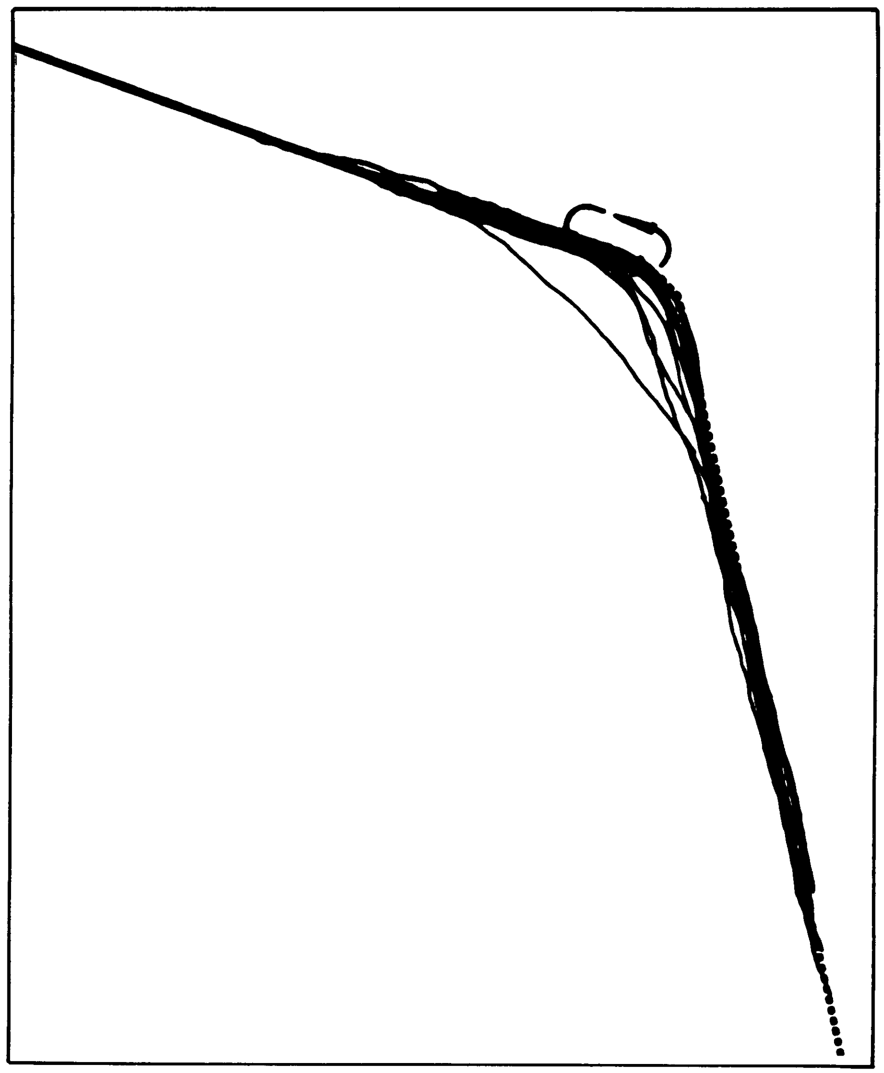


Figure 4.3 Case 3 Track Plots

rules of thumb regarding parameters such as climb, descent, and turn rates. Accelerations, decelerations and vertical path profiles are chosen arbitrarily or as a matter of convenience because pilots have no way to ascertain the effect of a particular choice on overall ATC flow. Such decisions regarding aircraft maneuvering can negatively affect the ability of a controller to precisely achieve metering and spacing objectives.

A TSD can provide the information necessary to enable the pilot to become an active element in the control process.

Given information about surrounding traffic and ATC control objectives, pilots will more often be able to regulate speed, altitude, and path profiles in a manner favorable to the overall traffic flow.

In other cases, when a basic clearance has been issued, pilots can assist in the control process by making small or minor corrections when necessary to achieve a desired traffic situation. Examples would be maintaining a desired separation behind another aircraft or following another aircraft through a simple path profile. By making use of the pilot's ability to precisely and continuously make corrections, the control process which now is "open loop" between radar vectors can be made "closed loop".*

A TSD could provide increased capability for computer-aided metering and spacing systems based on the "time to turn" concept. These are being designed for eventual implementation in the ARTS system. A pilot's ability to close the spacing control loop once a basic "time to turn" clearance has been issued can enhance the accuracy of the spacing process and provide flexibility for coping with system disturbances such as weather.

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* A closed loop process is one in which errors can be continuously detected, evaluated, and corrected.

A new class of instructions designated as "conditional clearances" may be employed to increase ATC efficiency. A controller could set up, in advance, maneuvers predicated on traffic constraints to be initiated by the pilot. An example of such a procedure would be the conditional cancellation of climb restrictions on a SID. A typical departure control clearance might read as follows:

> American 802 turn right to 360°, intercept the Merrimac 4 departure, cancel the 4000' climb restriction if able to remain clear of crossing traffic on Victor 431.

In this particular case, the pilot might determine that an adequate rate of climb could be maintained to pass well above the crossing traffic. An immediate climb which both meets ATC constraints and more closely approximates the optimal climb profile for the subject aircraft could be initiated. Block time and fuel consumption for the subject aircraft would be decreased and ATC could release the use of the airspace which was being reserved for the crossing restriction.

Test cases 4 through 8 were designed to test several examples of procedural changes based on the use of a TSD. An attempt was made to measure the performance accuracy for these various tasks along with pilot workload and communications volume.

A. Test Case 4

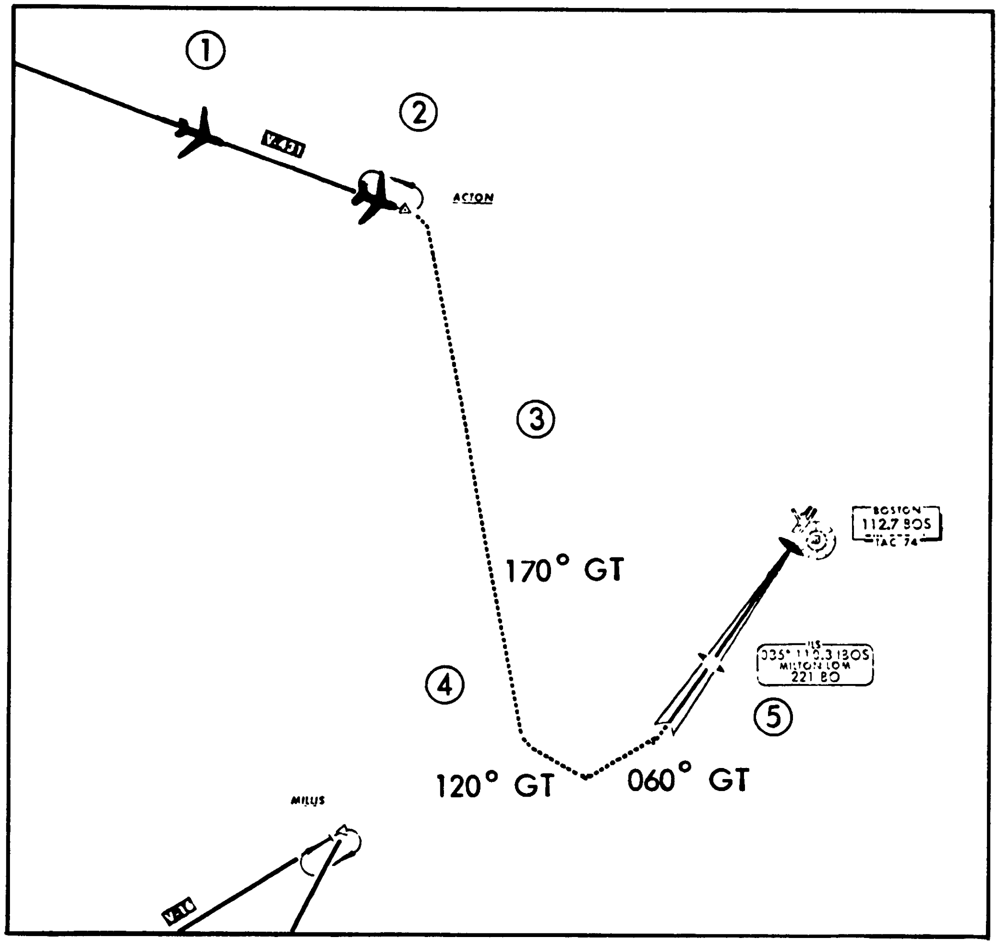
Case 4 investigates the use of a TSD in an ARTS III terminal area environment similar to that which will exist prior to implementation of ground based computer aided metering and spacing systems. A situation is tested in which pilots are asked to assist in the control process according to an impromptu clearance issued by the controller. The clearance contains instructions to attain and maintain a specific traffic situation via simple maneuvers involving speed and path corrections accomplished through use of a TSD.

In this environment, the controller transitions aircraft from enroute descent, draws aircraft from the holding patterns and assigns the landing sequence. Radar vectors would remain the primary means for initially positioning aircraft and for handling aircraft not equipped with a TSD.

Once the basic flow configuration has been established, TSD equipped aircraft could be cleared by the controller to follow in trail at a specified distance behind preceeding aircraft in the same flow or to acquire and merge behind aircraft in alternate flows or on final approach. Controllers would feed aircraft into the pattern, monitor aircraft in the flows and radar vector aircraft not equipped with a TSD. The flow could be modified by issuing amended clearances to TSD aircraft or by returning TSD aircraft to full or partial control through radar vectors.

A map showing the details of case 4 is given in Figure 4.4 The target aircraft in case 4 followed a profile based on an arrival flow from ACTON. Through simulated communications, the aircraft was radar vectored to the ILS via altitude, heading and speed instructions representative of those used in actual operations. The subject aircraft, which was TSD equipped, received the following clearances:

t = 0 sec	American 802 after Acton follow Eastern 477 6 nm. in trail, expect an ILS approach to runway 4R.
t = 320 sec	American 802 close spacing as Eastern 477 reduces speed, attain 4 nm. spacing at or before the time you reach the outer marker.



① Subject aircraft initial position

② Target aircraft initial conditions
6000'
200 knots
111° Ground track (GT)

③ Target aircraft ground track to runway 4R ILS

④ Target aircraft reduces speed to 160 knots and descends to 2000'

⑤ Target aircraft intercepts ILS and reduces to approach speed of 130 knots

Figure 4.4 Case 4 Layout

t = 360 sec American 802 descend to 1900'

t = 435 sec American 802 is cleared for an ILS approach to runway 4R behind Eastern 477, report the runway in sight.

Measurement parameters for case 4 were spacing accuracy on initial approach, delivery error at the outer marker, maneuvering airspace bounds, controller communications and pilot workload. Results for case 4 are shown in Table 4.5 and Figure 4.5

Case 4 results show that for the situation tested, pilots could consistently comply with the impromptu clearances and achieve accurate spacings on initial and final approach. Standard delivery errors at the outer marker of .08 nm. correspond to 2.5 sec errors in time at typical approach speeds. Pilot workload questionnaires and control history plots indicate that case 4 workload is well within acceptable limits for normal operations. Velocity records from the strip charts and position plots show smooth acquisition and tracking for the duration of the run.

Impromptu procedures, such as tested in case 4, in which no formal outline is available to controller or pilot previous to development of the situation, are important to ATC for providing flexibility. Such flexibility is needed to efficiently cope with disturbances such as runway changes, unforseen weather conditions, or ATC emergencies.

B. Radar Vector Comparison Test

As a comparison, the task performed in case 4 was accomplished without the use of a TSD in the subject aircraft. Radar vectors and other communications simulating the procedures which are currently used were given to both subject and target aircraft. For this test, a line ATC controller was asked to vector the subject aircraft using a simulated ARTS III display.

Table 4.5

Case 4 Results

Initial Spacing = 8 nm.

Initial Approach

Spacing, specified in clearance, for this phase of approach = 6 nm.

Mean steady state spacing of all subjects in this phase = 5.96 nm.

Maximum positive spacing bias for any subject = +.18 nm.

Maximum negative spacing bias for any subject = -.15 nm.

Best estimate of standard deviation of the population = .12 nm.

Spacing delivery error at the outer marker

Spacing, specified in clearance for final approach = 4 nm.

Standard spacing error at outer marker = .08 nm.

Maximum positive error for case 4 = +.06

Maximum negative error for case 4 = -.18

Response of Subject Pilots to Workload Questionnaire - Case 4

Choice of alternatives by percentage	The phrase which best describes the overall mental and physical workload of flying the aircraft through the required task is:
0%	A. Unacceptable: Workload is unacceptably high for routine operations — concentrated pilot attention to the exclusion of other essential tasks is required.
9%	B. Tolerable: Workload is high but tolerable — a considerable amount of pilot attention is focused on the task, however, all essential cockpit functions and most secondary cockpit functions can be completed on schedule in normal operations. Undesirable distractions from the performance of other cockpit tasks are frequent.
64%	C. Satisfactory: The overall mental and physical workload experienced during this task is not significantly different than that expected in a routine cockpit environment.
27%	D. Improved: There is a decrease in overall pilot workload from that usually experienced in this phase of flight.

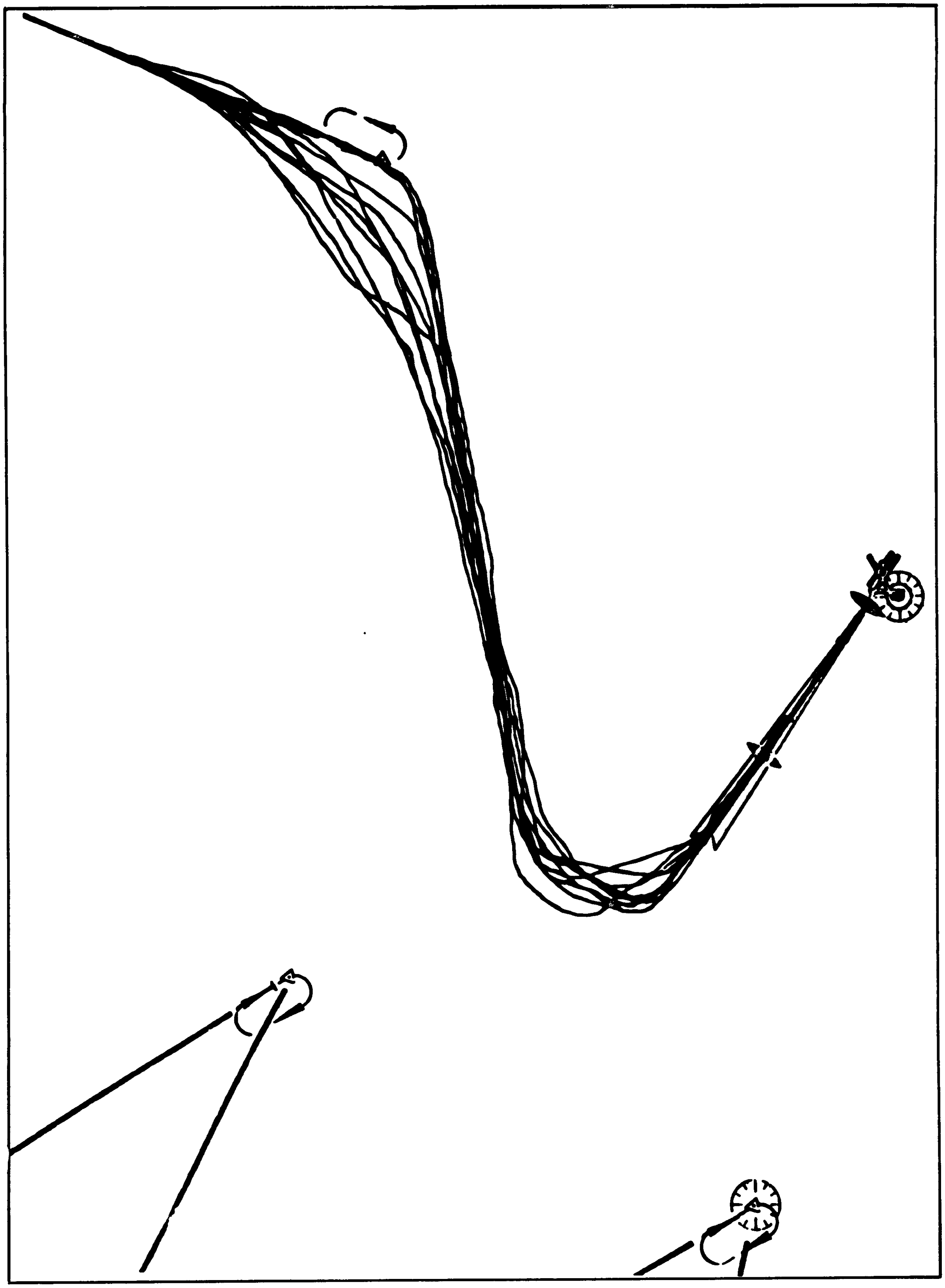


Figure 4.5 Case 4 Track Plots

An attempt was made to vector the aircraft to accuracy standards equivalent to those employed in normal operations. In a pre-run briefing, the controller was instructed to use standard communication phraseology appropriate for the situation.

As a further check on case 4 results, similar aircraft operations were observed in the Boston TRACON. Data was collected through monitoring the West sector controller's radar scope and radio frequencies. Results of the comparison test and the data recorded during observation of the actual terminal area operations are presented with case 4 results in Table 4.6.

The increased communications time and number of communications in the radar vector spacing test, compared to actual data, is largely attributed to the tendency of the subject controllers to exercise special care in setting up spacings due to motivation to perform well in the test environment. Another contributing factor was that more attention could be concentrated on the subject aircraft than would be possible in actual cases where up to 7 other aircraft would have to simultaneously be handled. Generally, however, the results of the radar vector comparison test are consistent with the Boston TRACON data.

Table 4.6

Comparison of Spacing Performance and Communications with and without a TSD

	1	2	3	4	5
	Case 4(with TSD)	Radar Vector Simulation (no TSD)	Comparison of Columns 1 and 2	Data Recorded in Actual Operations	Comparison of Columns 1 and 5
Total number of controller initiated communications (mean for subject aircraft)	4	13	69% decrease if a TSD is used	10	60% decrease if a TSD is used
Cumulative communications time (mean time for controller transmissions to the subject aircraft)	25 sec	74 sec	66% decrease if a TSD is used	55 sec	55% decrease if a TSD is used
Average spacing error at the outer marker	.08 nm.	.27 nm.	70% decrease if a TSD is used	.30 nm.	73% decrease if a TSD is used

The comparison outlined in Table 4.6 clearly indicates that communications volume can be reduced and that spacing accuracy can be improved through use of a TSD.

C. Test Case 5

Many different types of ATC procedures based on TSD capability show promise for increasing the capacity of terminal area operations. As an example, one such procedure was developed and tested in this simulation program. Case 5 investigates the use of a TSD in conjunction with predetermined arrival routings. As a basis for the new procedure, several standard terminal arrival routes (STAR's) similar to those already in use in several other major terminal areas were established. The Boston STAR's, however, were specifically designed for aircraft having TSD capability. Unlike current arrivals, these STAR's additionally define transition routings from the holding fixes to a specific runway. Common approach speeds are defined and included as part of the procedure. The transition routes are based on ground referenced paths over which controllers now vector aircraft for approach. These routes serve as the nominal approach path for aircraft transitioning from the holding fixes to the landing runway. Controllers clear aircraft via a specific arrival and transition route for the approach without any radar vectoring. Landing sequences are assigned as aircraft depart the holding fix. The pilot of the nth landing aircraft identifies the (n-1)th aircraft in the sequence and, using speed and path control within predetermined bounds, maneuvers to satisfy the spacing constraints outlined in the clearance.

The procedure is defined in both text and graphical form on approach plates and selected information such as transition routes are also displayed on the TSD. A diagram of the hypothetical procedure which was developed for Boston's runway 4R is shown in Figure 4.6.

The case 5 traffic profile was based on an Acton routing. The subject aircraft was given clearances as follows:

t = 0 sec	American 802 is cleared for the Acton One arrival with a runway 4R transition, follow Eastern 477 6 nm. in trail.
t = 320 sec	American 802 close spacing as Eastern 477 slows, attain 4 nm. spacing at or before the time you reach the outer marker. Descend to 1900'.
t = 460 sec	American 802 is cleared for an approach to runway 4R behind Eastern 477, report having runway in sight.

The results of case 5 are shown in Table 4.7 and Figure 4.7.

Procedures of this type would be used primarily for high capacity runways at major terminals where most aircraft would be TSD equipped. Unequipped aircraft would continue to be radar vectored through the system to landings on adjacent runways. At the controller's discretion, unequipped aircraft could be included in the primary flow if traffic densities and workload permit.

Case 5 results can also be compared with the radar vector comparison test since a similar arrival profile was used. Again, significant reduction in communications and spacing errors can be noted.

D. Test Case 6

Case 6 investigates a merging situation in which aircraft are being fed from both the Millis and Whitman holding fixes to the runway 4R approach. A dual approach controller configuration is assumed in which aircraft in the Millis and Whitman flows are handled by different controllers using

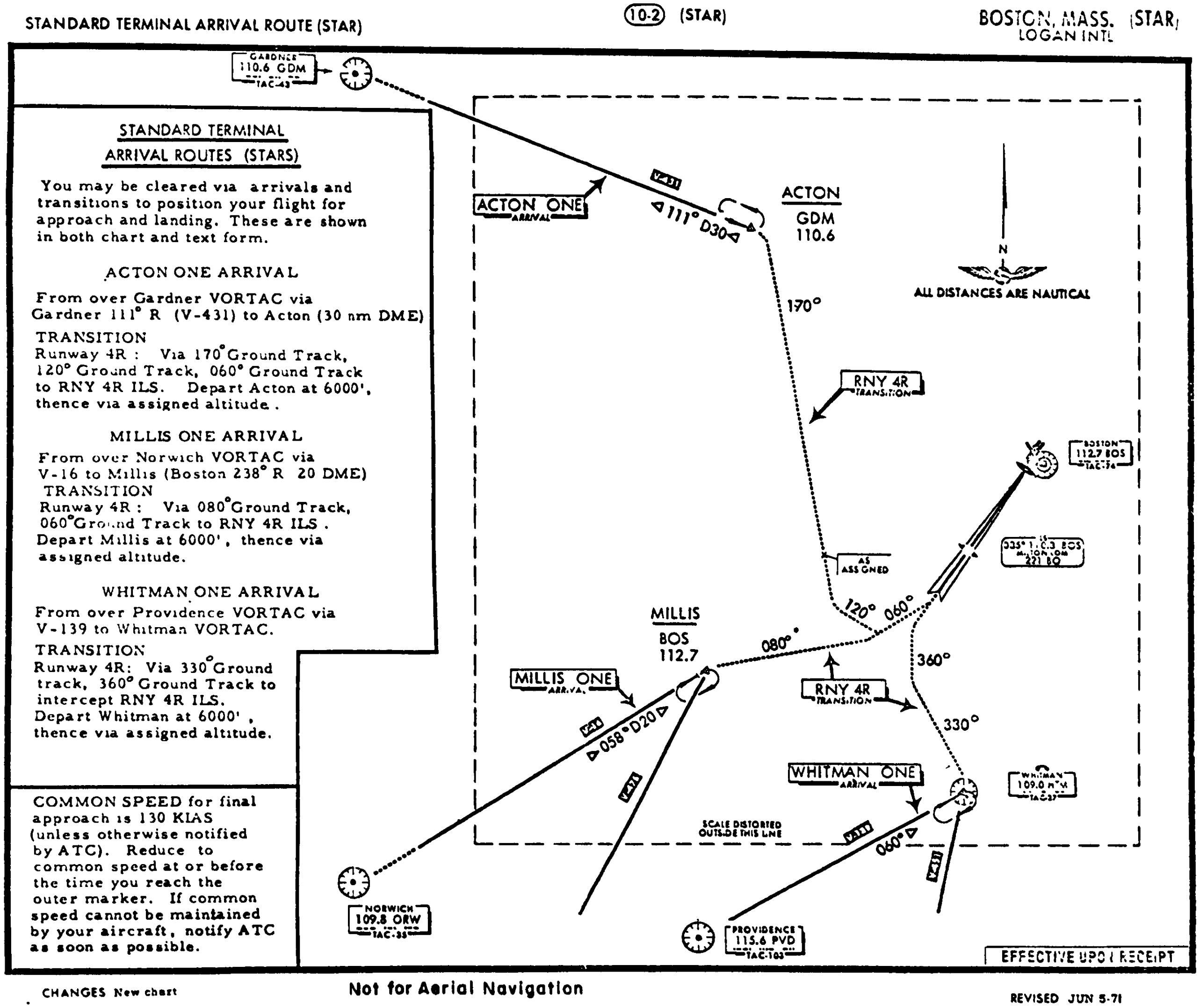


Figure 4.6 TSD STAR Procedure Tested in Case 5

Table 4.7

Case 5 Results
Initial Spacing = 8 nm. Initial Approach Spacing, specified in clearance, for this phase of approach = 6 nm. Mean steady state spacing of all subjects in this phase = 5.97 Maximum positive spacing bias for any subject = .33 Maximum negative spacing bias for any subject = -.28 Best estimate of the standard deviation of the population = .15 Spacing Delivery Error at the Outer Marker Spacing, specified in clearance, for final approach = 4 nm. Standard spacing error at outer marker = .06 Maximum positive error for case 5 = .04 Maximum negative error for case 5 = -.16

Response of Subject Pilots to Workload Questionnaire - Case 5	
Choice of Alternatives by percentage	The phrase which best describes the overall mental and physical workload of flying the aircraft through the required task is:
0%	A. Unacceptable: Workload is unacceptably high for routine operations — concentrated pilot attention to the exclusion of other essential tasks is required.
9%	B. Tolerable: Workload is high but tolerable — a considerable amount of pilot attention is focused on the task, however, all essential cockpit functions and most secondary cockpit functions can be completed on schedule in normal operations. Undesirable distractions from the performance of other cockpit tasks are frequent.
64%	C. Satisfactory: The overall mental and physical workload experienced during this task is not significantly different than that expected in a routine cockpit environment.
27%	D. Improved: There is a decrease in overall pilot workload from that usually experienced in this phase of flight.

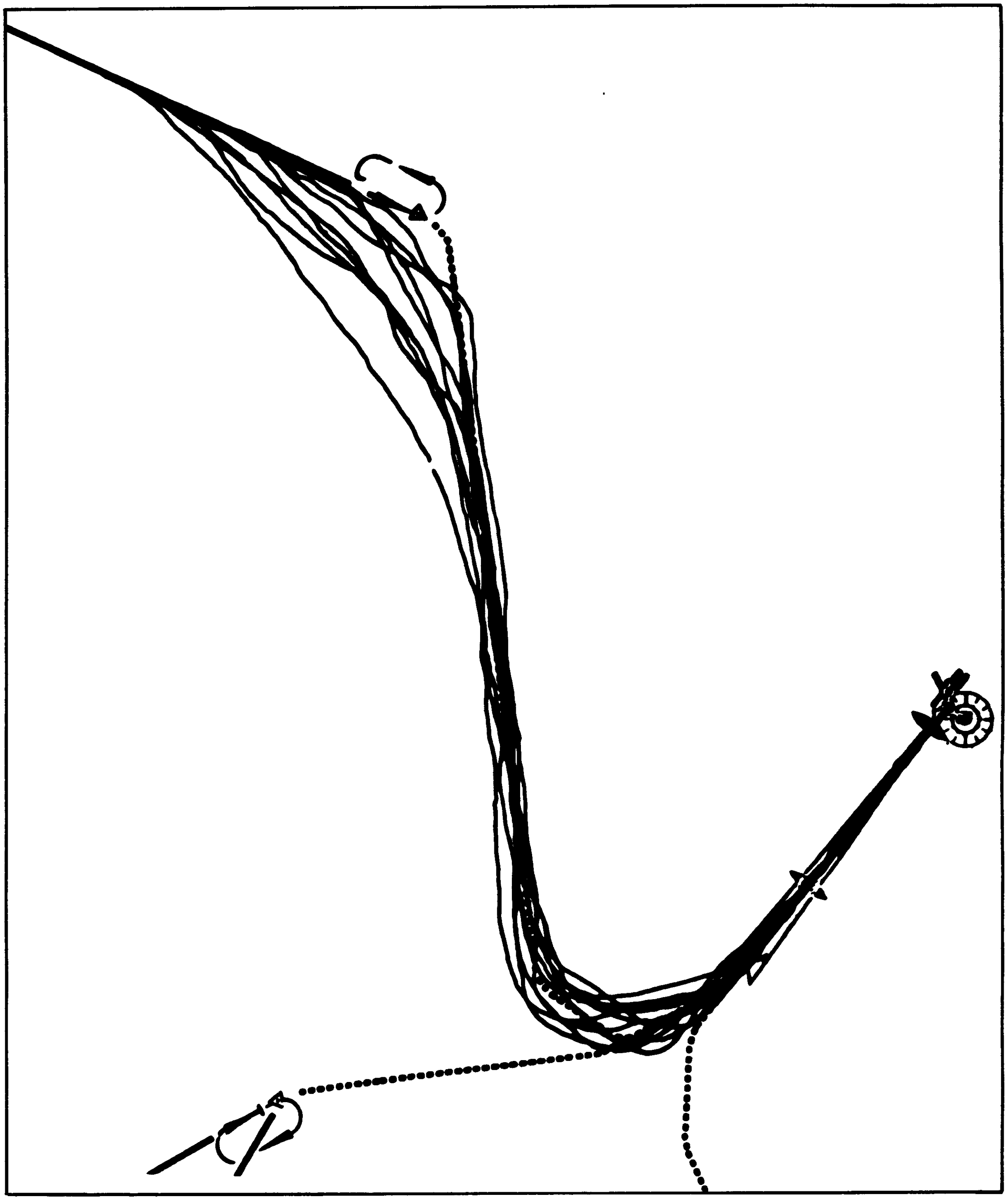


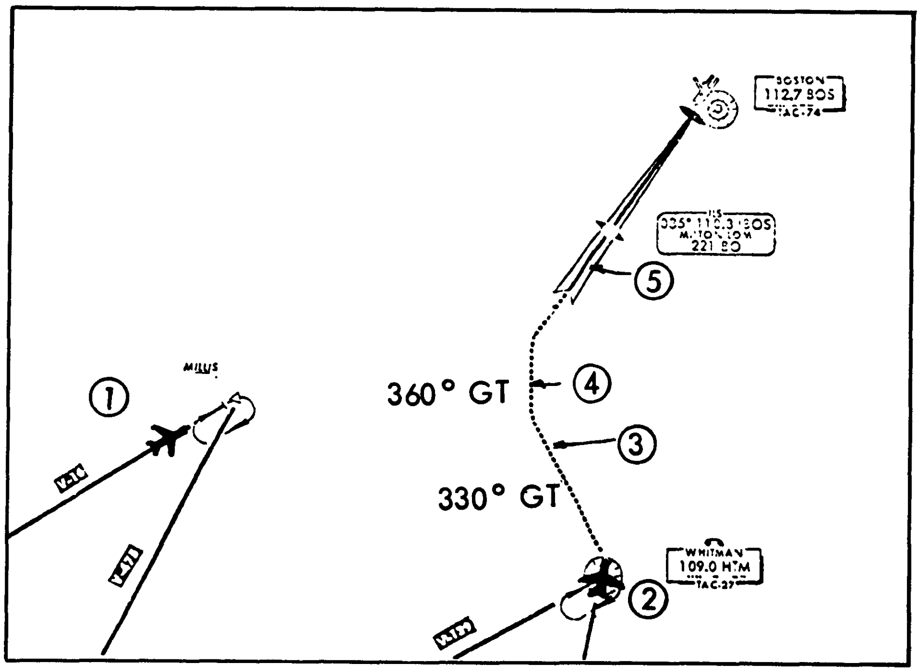
Figure 4.7 Case 5 Track Plots

separate radio frequencies. The dual approach controller configuration was chosen because it represents a difficult case in present operations in which the pilots of aircraft in one flow cannot monitor the clearances of aircraft in the other flow which is being merged for final approach.

Since different frequencies are used, pilots are only generally aware of other aircraft being present, unless controllers issue specific advisory messages. In this type of operation, present spacing accuracies are often degraded and vectoring is more difficult because the West sector controller (Millis) must vector traffic with respect to targets under the East sector controller's (Whitman) jurisdiction and vice versa. Coordination for sequencing and merging of the East and West sector traffic usually is accomplished in the radar room by the respective controllers, and a run coordinator.

In the situation simulated in case 6, shown in Figure 4.8 a target aircraft departs Whitman at 6000' for the ILS to runway 4R viá a typical radar vectored path for this approach. The pilot of the subject aircraft is given a clearance to identify, merge behind the target aircraft and establish a 4 nm.spacing in trail for the final approach through use of the TSD. The results of case 6 are given in Table 4.8 and Figure 4.9.

Case 6 demonstrated that pilots can perform merging tasks without excessive maneuvering or speed adjustments, at acceptable workload levels. No general tendency to overshoot the desired spacing (space at a distance less than 4 miles) was observed. Pilot judgement in this case was consistently good. Proper lead angles and required speed differentials were easily determined through rules of thumb based on the targets apparent drift angle and drift rate relative to the subject aircraft.



① Subject aircraft initial conditions
6000'
200 knots
058° heading

② Target aircraft initial conditions
6000'
200 knots

③ Target profile from Whitman to runway 4R ILS

④ Target reduces speed from 200 knots to 160 knots

⑤ Target reduces to 130 knots for approach

Figure 4.8 Case 6 Layout

Table 4.8

Case 6 Results	
Acquisition	
Mean time to acquire 90% of final spacing	183.2 sec
Spacing Delivery, Error at the Outer Marker	
Spacing specified in clearance for final approach	4 nm.
Standard spacing error at outer marker	.09
Maximum positive error for case 6	+.08
Maximum negative error for case 6	-.21

Response of Subject Pilots to Workload Questionnaire - Case 6

Choice of alternatives by percentage	The phrase which best describes the overall mental and physical workload of flying the aircraft through the required task is:
0%	A. Unacceptable: Workload is unacceptably high for routine operations — concentrated pilot attention to the exclusion of other essential tasks is required.
10%	B. Tolerable: Workload is high but tolerable — a considerable amount of pilot attention is focused on the task, however, all essential cockpit functions and most secondary cockpit functions can be completed on schedule in normal operations. Undesirable distractions from the performance of other cockpit tasks are frequent.
50%	C. Satisfactory: The overall mental and physical workload experienced during this task is not significantly different than that expected in a routine cockpit environment.
40%	D. Improved: There is a decrease in overall pilot workload from that usually experienced in this phase of flight.

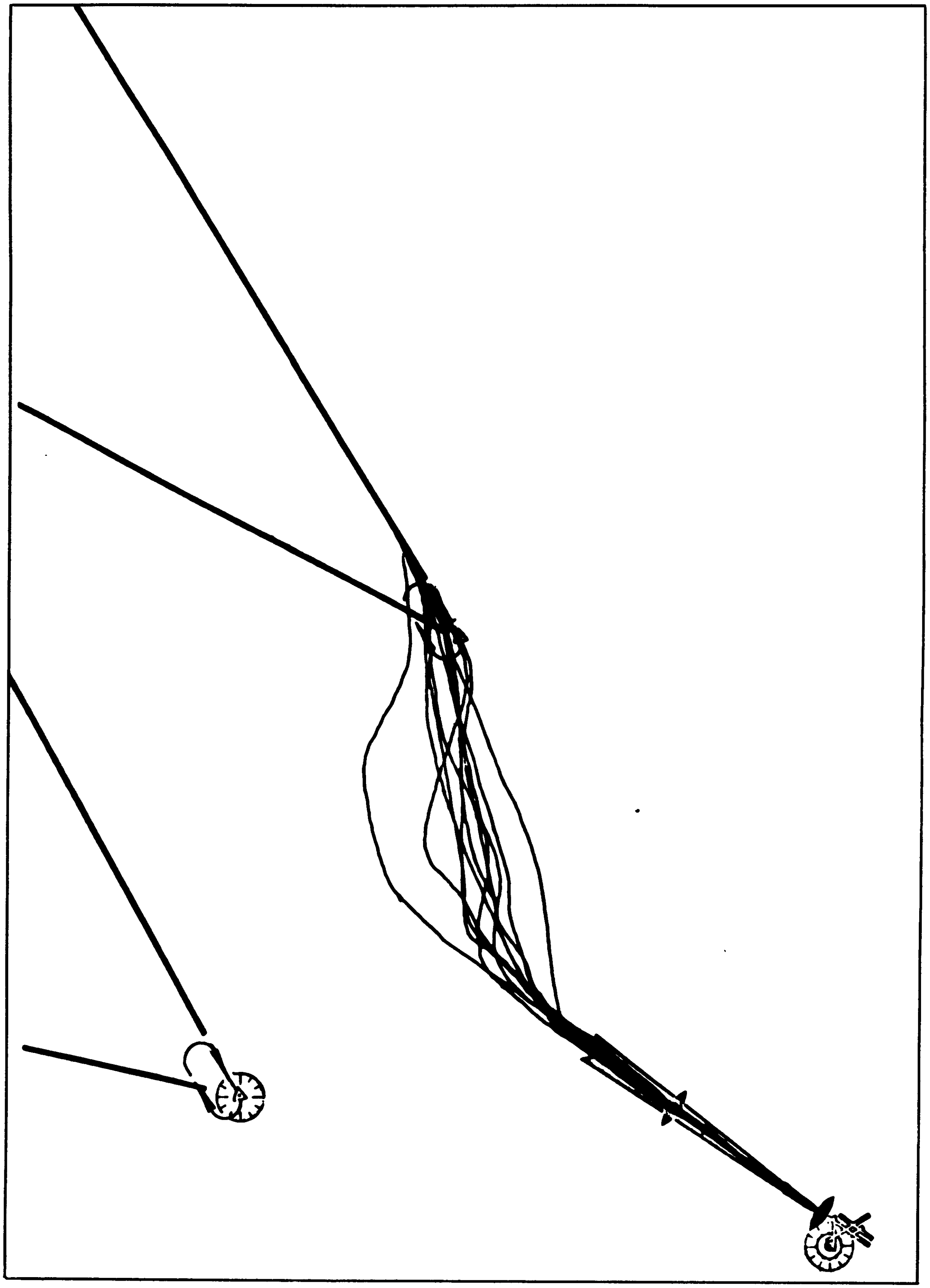


Figure 4.9 Case 6 Track Plots

It is believed that the ease with which pilots were able to perform this task is largely due to experience gained in simular operations presently performed in VFR.

E. Test Case 7

Case 7 simulates operations employing the box or trombone traffic pattern in instrument conditions through use of a TSD. The procedure tested in this case is analogous to the standard visual traffic pattern which provides high capacity operations in good weather.

The subject aircraft is initially positioned on a downwind leg, 3 miles abeam the airport at 2000'. The task is to space behind and follow a target aircraft which starts 8 nm. from the outer marker on final approach. The following clearance is issued to the subject aircraft:

> American 802 is cleared for approach behind
> Eastern 477, maintain 3 nm. spacing on final.

Initial conditions for the case were chosen so that the subject pilot is presented with a maximum difficulty task. Aircraft initial positions and velocities lead to performance of the base leg turn at or near the outer marker. The subject pilot must execute a complete course reversal which both achieves proper spacing and smoothly intercepts the localizer and glide slope for a stabilized approach. At the same time the aircraft must be configured for landing. This case represents a difficult task which approaches the limit which a pilot can be expected to routinely perform in current generation aircraft.

Results of case 7 are presented in Table 4.9 and Figure 4.10

The spacing results and path records from case 7 show that even in this difficult case, pilots were able to successfully accomplish the task.

Table 4.9

Case 7 Results

Spacing delivery error at the outer marker

Spacing specified in clearance for final approach	3 nm.
Standard spacing error at the outer marker	.23
Maximum positive spacing error	.5
Maximum negative spacing error	-.39

Response of Subject Pilots to Workload Questionnaire - Case 7

Choice of alternatives by percentage	The phrase which best describes the overall mental and physical workload of flying the aircraft through the required task is:
0%	A. Unacceptable: Workload is unacceptably high for routine operations — concentrated pilot attention to the exclusion of other essential tasks is required.
27%	B. Tolerable: Workload is high but tolerable — a considerable amount of pilot attention is focused on the task, however, all essential cockpit functions and most secondary cockpit functions can be completed on schedule in normal operations. Undesirable distractions from the performance of other cockpit tasks are frequent.
46%	C. Satisfactory: The overall mental and physical workload experienced during this task is not significantly different than that expected in a routine cockpit environment.
27%	D. Improved: There is a decrease in overall pilot workload from that usually experienced in this phase of flight.

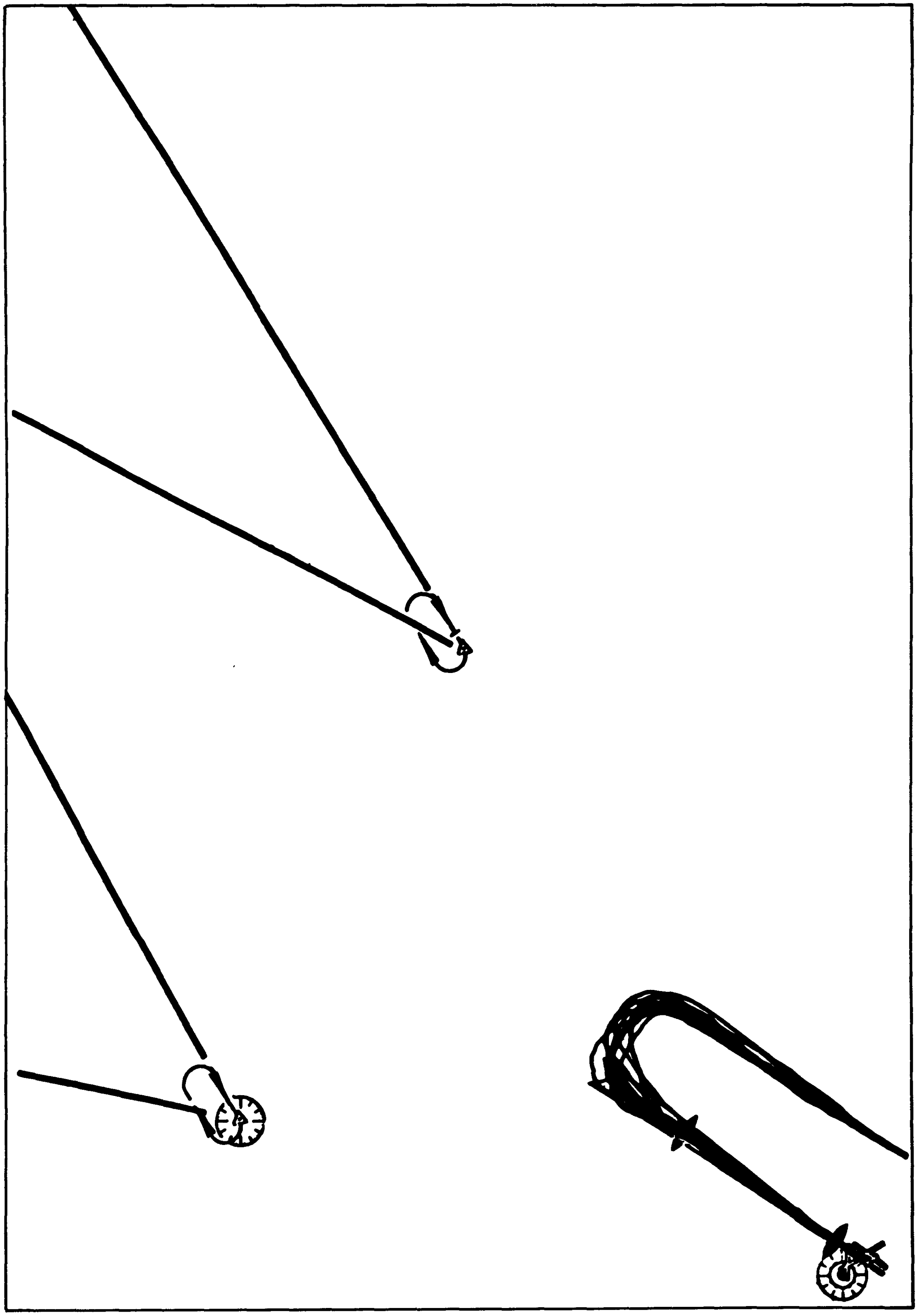
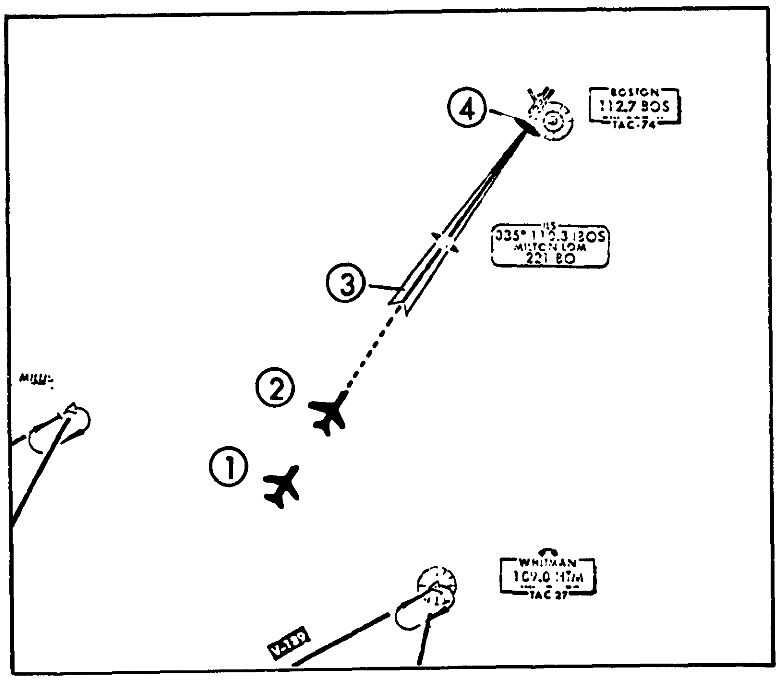


Figure 4.10 Case 7 Track Plots

Implications of successful performance in case 7 is that a procedure using radar vectors to the traffic pattern could be employed in any weather. This procedure is quite important because it permits the flexibility necessary to operate a runway at full capacity. By extending or shortening the downwind leg,a pilot can easily control the spacing to be achieved behind a proceeding aircraft. Ability to provide time flexibility by turning on base leg and final approach earlier or later than normal can be used to take full advantage of a runway which is vacated sooner than expected. Alternatively, slight delays can be accommodated without the necessity for a waveoff command or a change in sequence.

F. Test Case 8

Case 8 investigates spacing judgement and the psychological aspects of pilot assurance and assessment of safety. A task was selected which involves aircraft operations at minimal longitudinal separations on final approach and landing. Pilots of the subject aircraft were asked to achieve minimum spacing behind an aircraft on final approach consistent with their personal assessment of safety, while maintaining a low probability of a go-around (see Figure 4.11). For this experiment,a go-around was required if the subject aircraft arrived at the Category II decision height of 100' before the target aircraft cleared the runway. Case 8 assumes the existence of an upgraded surveillance capability which maintains coverage at low altitudes and on the airport surface. Such capability could be achieved by including airport surface detection radar (ASDE) or similar system inputs in the TSD data base. The preceeding aircraft was assumed to be a smaller aircraft (DC-9) than the subject aircraft (B707) so that wake turbulence considerations for establishing spacing criteria could be minimized.



(1) Subject aircraft initial conditions
2000'
180 knots
035° heading

(2) Target aircraft initial conditions
2000'
160 knots
035° heading

(3) Target aircraft intercepts and tracks ILS for approach

(4) Missed approach is required at the 100' decision height if the target aircraft is not clear of the runway

Figure 4.11 Case 8 Layout

Generally, subject pilots determined the minimum spacing at which they could safely operate by applying experience based on VFR situations to this task. Several subjects also performed a mental calculation based on approach speed and expected runway occupancy time of the target aircraft to determine the minimum spacing which would satisfy the go-around constraint. In data sessions, all subjects were successful in completing case 8 without a go-around.

Results of case 8 are presented in Table 4.10.

Upon completion of case 8, subject pilots were asked to comment on their personal feelings regarding use of longitudinal separations less than 3 nm. for final approach and landing. A summary of post run comments is given in Table 4.11.

The two subjects who agreed with statement 1 were military pilots accustomed to operating regularly with more than one aircraft on the runway.

Results of case 8 indicate that significant changes in separation standards could be made which would provide increased capacity in certian conditions. Landing/landing spacings, as tested in case 8, takeoff/takeoff, and takeoff/landing separations could be decreased to values comparable to those used in visual conditions. The importance of these changes to separation standards is very great because in many cases they would enable operations to be conducted in instrument conditions on intersecting runways.

Table 4.10

Case 8 Results

Subject	Spacing as Target Aircraft Passed Outer Marker	Spacing as Target Aircraft Passed Runway Threshold*	Spacing as Target Aircraft Taxis Clear of Runway
1	3.4	2.8	1.8
2	3.3	2.6	1.9
3	3.0	2.6	1.7
4	3.4	2.6	1.7
5	3.4	2.6	1.3
6	3.5	2.0	1.2
7	3.5	2.7	2.0
8	3.3	2.5	1.7
9	3.2	2.3	1.7
10	3.4	2.2	1.3

* Critical Spacing — minimum steady state spacing for completion of task without missed approach was about 2.1 nm.

Response of Subject Pilots to Workload Questionnaire - Case 8	
Choice of alternatives by percentage	The phrase which best describes the overall mental and physical workload of flying the aircraft through the required task is:
0%	A. Unacceptable: Workload is unacceptably high for routine operations — concentrated pilot attention to the exclusion of other essential tasks is required.
18%	B. Tolerable: Workload is high but tolerable — a considerable amount of pilot attention is focused on the task, however, all essential cockpit functions and most secondary cockpit functions can be completed on schedule in normal operations. Undesirable distractions from the performance of other cockpit tasks are frequent.
55%	C. Satisfactory: The overall mental and physical workload experienced during this task is not significantly different than that expected in a routine cockpit environment.
27%	D. Improved: There is a decrease in overall pilot workload from that usually experienced in this phase of flight.

Table 4.11

Case 8 Subject Comment Summary

Statement #		
1	2 subjects agreed 8 subjects disagreed	Neglecting wake turbulence considerations, separations on final approach as low as 2 miles can be safely employed in instrument conditions with present ATC control methods, communications and equipment.
2	9 subjects agreed 1 subject disagreed	With traffic information such as provided by a TSD in case 8, longitudinal separations as low as 2 miles could be routinely used for final approach in instrument conditions.
3	other comment	Similar display should be available to crash equipment for finding disabled aircraft in bad weather.
4	other comment	If proper scale selection and data were available, this display would be useful for planning runway turnoffs or taxiing in bad visibility or at night.
5	other comment	With a display of this type, operations could be safely conducted with more than one aircraft on the runway at the same time.

This would permit increases of capacity at many airports which presently have intersecting runways that cannot be fully used in instrument weather.*

4.3 Position Command Spacing Tests

Cases 9 and 10 investigate extended use of the TSD for display of guidance commands for control of aircraft in the terminal area. The commands would be generated by the ground based computer and uplinked to the respective aircraft. The desired position for a particular aircraft would be displayed as a special symbol on the TSD called a "bug" or "bucket" moving along the desired path to the ILS. The pilot would maneuver his aircraft via the TSD to attain and maintain the position indicated by the command bug for the entire approach. Algorithms in the ground computer which generate these command bugs would be designed to satisfy the appropriate merging and spacing constraints which apply to the situation. Also considered would be wind, weather, and aircraft limitations such as maneuvering speed range, feasible turn, climb and descent rates, and final approach speed.

A. Test Case 9

Case 9 models a situation in which the "buckets" originate on the localizer centerline 15 miles from the outer marker (Figure 4.12) spaced appropriately for the desired runway acceptance rate. Several aircraft would be drawn from the holding fixes at different altitudes and assigned to

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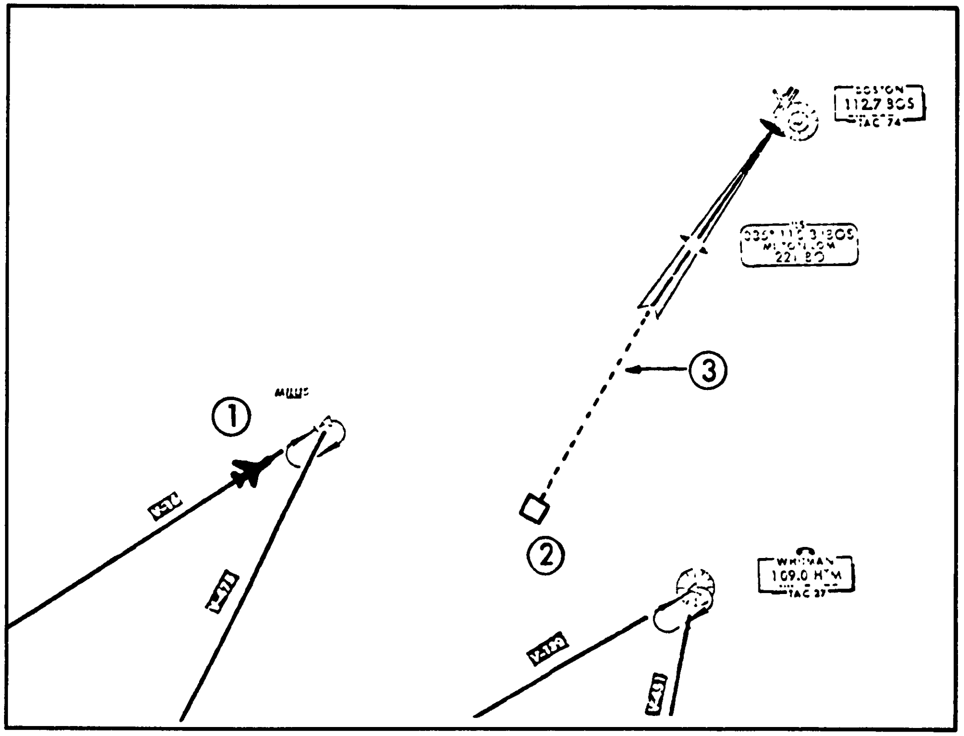
* Many airports such as LaGuardia or Washington National do not have land available for construction of parallel runways which could be used for simultaneous instrument approaches. At such locations, one of the few methods which can be employed to increase capacity is to take full advantage of intersecting runways.



1 Subject aircraft initial position

2 Command bug initial position

3 Track followed by command bu
for final approach

Figure 4.12 Case 9 Layout

intercept and track a particular command bug. Once the aircraft were established in their respective slots, descent clearance to a common altitude or to the initial approach altitude could be issued.

Case 9 considers the performance of a single aircraft in this type of task. The subject aircraft was initially positioned approaching the Millis holding fix at 6000'. Clearance was issued to intercept and track the command bug for final approach. Results of case 9 are presented in Table 4.12 and Figure 4.13.

B. Test Case 10

Case 10 models a situation in which the command bug follows a profile throughout an entire approach. The bugs would sequentially originate in the vicinity of the holding fixes and follow paths which are compatible with other arrival, departure and airway routings.

In case 10 (Figure 4.14) the command bug started on the inbound leg of the holding pattern, made one circuit of the pattern then followed the Millis 4R transition route outlined in the STAR referenced in case 5. The subject aircraft was required to acquire the bug before departing the holding fix for approach by flying an abbreviated or extended holding pattern or by speed control.

Results of case 10 are given in Table 4.13 and Figure 4.15.

Results of cases 9 and 10 (tracking a command bug) indicate that accurate delivery at the outer marker can alternatively be achieved by display of command information on the TSD. Case 10 additionally shows that very precise path control can be maintained on arrival routings. All normal operations from Millis could have been conducted in a 2 nm. wide corridor. However, in cases 9 and 10 workload appeared to be marginally high for

Table 4.12

Case 9 Results		
Acquisition		
Mean time to acquire command bug	141.6 seconds	
Maximum time to acquire	170.0	
Minimum time to acquire	118.0	
Delivery error at outer marker		
Standard error of arrival at outer marker		.18 nm.
Maximum spacing error at outer marker		.34 nm.

Response of Subject Pilots to
Workload Questionnaire - Case 9

Choice of alternatives by percentage	The phrase which best describes the overall mental and physical workload of flying the aircraft through the required task is:
0%	A. Unacceptable: Workload is unacceptably high for routine operations — concentrated pilot attention to the exclusion of other essential tasks is required.
36%	B. Tolerable: Workload is high but tolerable — a considerable amount of pilot attention is focused on the task, however, all essential cockpit functions and most secondary cockpit functions can be completed on schedule in normal operations. Undesirable distractions from the performance of other cockpit tasks are frequent.
28%	C. Satisfactory: The overall mental and physical workload experienced during this task is not significantly different than that expected in a routine cockpit environment.
36%	D. Improved: There is a decrease in overall pilot workload from that usually experienced in this phase of flight.

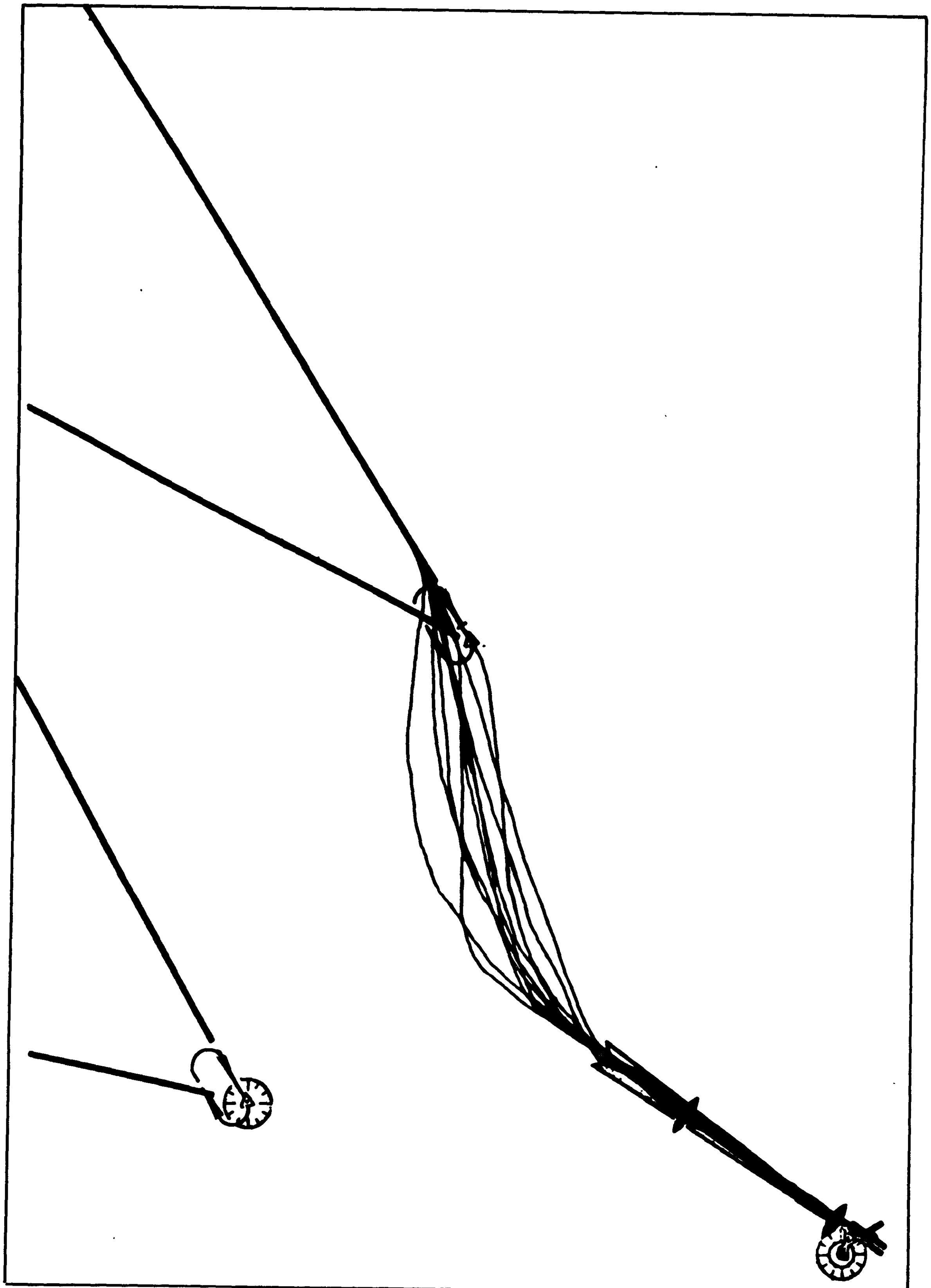
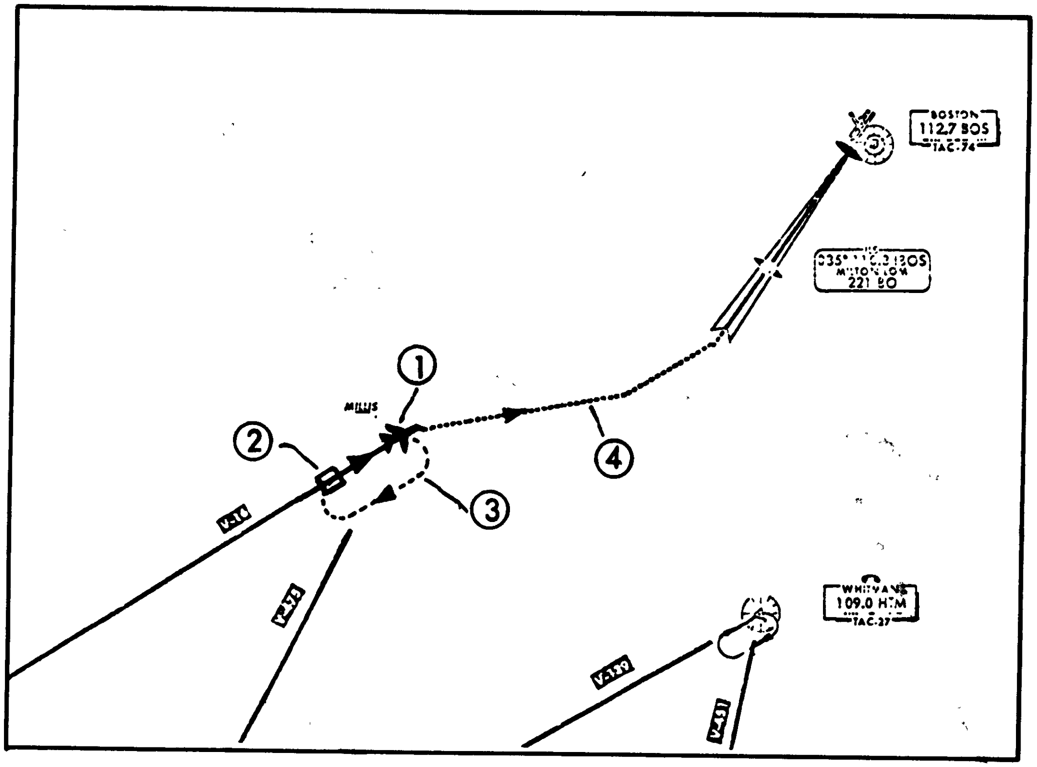


Figure 4.13 Case 9 Track Plots



① Subject aircraft initial position (beginning outbound turn in holding pattern)

② Command bug initial position

③,④ Command bug holding pattern and track to ILS 4R approach

Figure 4.14 Case 10 Layout

Table 4.13

Case 10 Results

Acquisition

All subjects but 1 acquired the command bug before departing Millis (see note on case 10 track plot - Fig. 4.15)

Approach

Mean spacing error of population from command bug = .19 nm.

Delivery error at outer marker

Standard error = .09 nm.

Maximum error = .18 nm.

Response of Subject Pilots to Workload Questionnaire - Case 10

Choice of alternatives by percentage	The phrase which best describes the overall mental and physical workload of flying the aircraft through the required task is:
0%	A. Unacceptable: Workload is unacceptably high for routine operations — concentrated pilot attention to the exclusion of other essential tasks is required.
40%	B. Tolerable: Workload is high but tolerable — a considerable amount of pilot attention is focused on the task, however, all essential cockpit functions and most secondary cockpit functions can be completed on schedule in normal operations. Undesirable distractions from the performance of other cockpit tasks are frequent.
20%	C. Satisfactory: The overall mental and physical workload experienced during this task is not significantly different than that expected in a routine cockpit environment.
40%	D. Improved: There is a decrease in overall pilot workload from that usually experienced in this phase of flight.

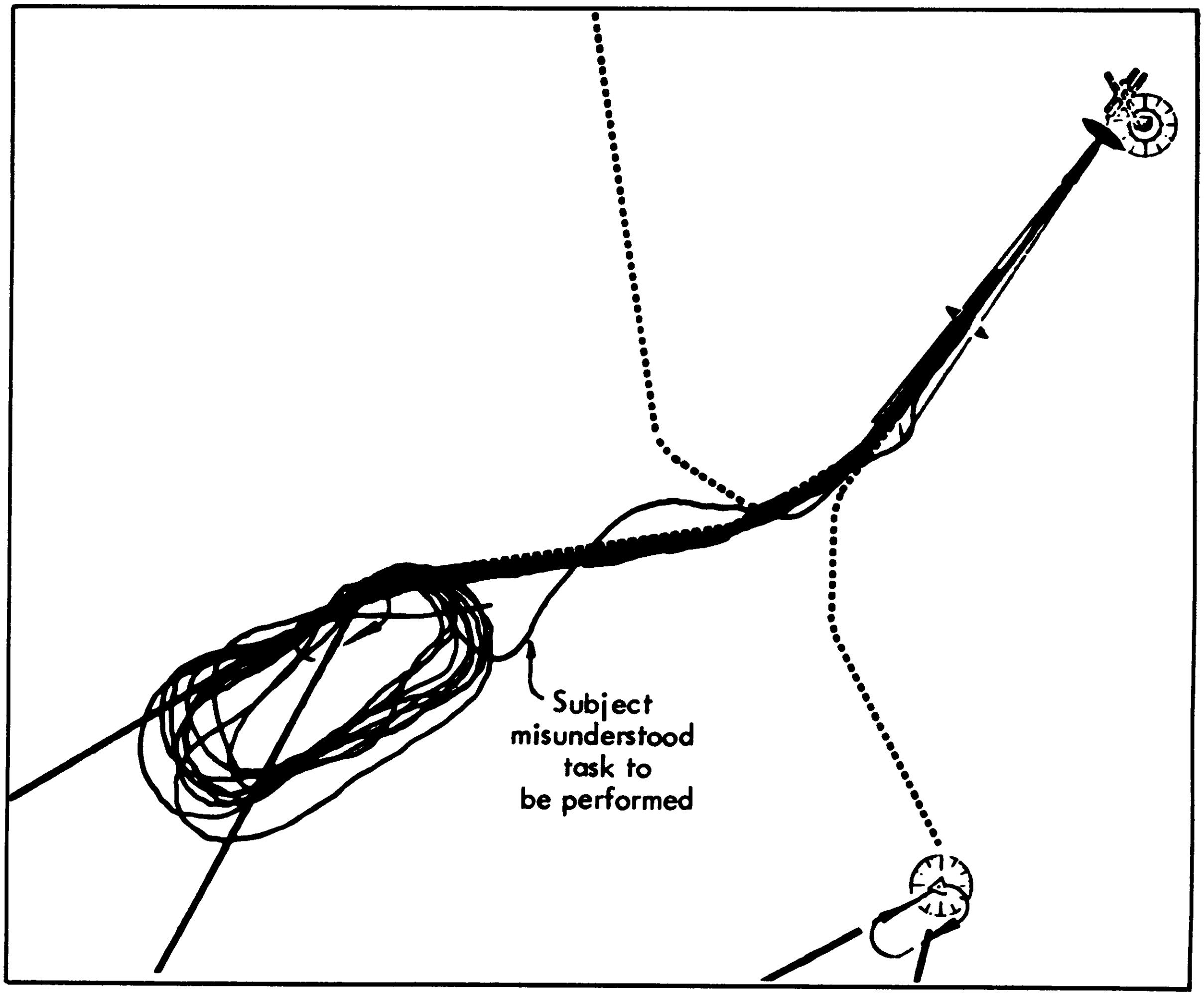


Figure 4.15 Case 10 Track Plots

normal operations. Manual control in procedures of this type would most likely be reserved for backup in the event of failure of an autopilot system.

Modified command bug procedures, however, may be able to meet both accuracy and workload requirements. By relaxing constraints so that conformance is necessary only at specified points such as crossing restrictions and the outer marker,instead of along the entire path,workload can be kept at acceptable levels.

Command data, as tested in cases in 9 and 10, would primarily be used for situations such as coordination of mixed takeoff and landing operations or operations from intersecting runways.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

5.1 Summary of Conclusions

Results of the test program were generally quite promising. Although only a limited number of situations were tested, spacing accuracies, pilot and controller workload, and subject pilot comments indicate that the TSD can make a significant contribution to increasing safety, efficiency and capacity in the ATC process.

Spacing accuracies on the order of .1 nm (1-sigma) were demonstrated in a variety of tracking and merging situations. Delivery errors at the outer marker were well within the 5 second (1-sigma) bounds specified by the DOT Air Traffic Control Advisory Committee[3] for future ATC systems.

Acquisition and merging problems were handled smoothly without repeated course reversals or corrections. Closure to the desired spacing was accomplished asymptotically in most test runs. Overshoots which occurred were generally less than .2 nm and were promptly corrected.

Pilot overall workload ratings for the various cases varied from "improved" to "tolerable". Improved ratings generally reflected a belief that a TSD would cut down communications with the controller, simplify procedures involving complicated climb, descent and crossing restrictions such as encountered on SID's and STAR's, and enable the pilot to more effectively plan for aircraft management. Cases 1 through 8 (all except command bug cases) were generally rated as being "satisfactory" from a workload standpoint. Plots of control movement indicated that amplitude of input and frequency of control reversals encountered in the spacing tasks were comparable with those experienced when under radar vector control in the terminal area. Pilots generally commented that workload levels were about the same as normally experienced in terminal area operations. However, in cases 9 and 10 (command bug tests) 30% of the subject pilots responded that workload levels were "tolerable" (as defined in the workload questionnaire). To keep pilot workload at acceptable levels in these cases, modified procedures with less restrictive constraints must be employed.

Surveys of subject opinion strongly indicated that a TSD could provide increased safety in the air traffic control process by:

1. Enhancing the pilot's ability to sight and avoid other traffic in marginal visual conditions.
2. Providing a means to monitor separations in instances where aircraft are closely spaced-such as on parallel ILS approaches.
3. Enabling the pilots to crosscheck ATC clearances issued to their own and other aircraft.

Comparison of the cases in which a TSD was available to the pilot with actual operations and with the comparison test case, which relied exclusively on radar vectors, indicated that significant decreases in controller workload are feasible. Improved workload results from the reduced need for radar vectors, speed instructions, and advisory messages.

It was also found that controller's instructions could be simplified and abbreviated without sacrificing essential content of the message.

In test cases using a TSD, the total number of messages and the cumulative communications time decreased by more than 60% when compared with data taken in the simulated radar vector tests or with the data recorded at the Boston TRACON during actual operations.

5.2 Implications to ATC Capacity

Test case performance indicates that TSD's can contribute to increases in ATC system capacity. The TSD traffic picture extends the senses of the pilot in such a way that high capacity metering and spacing procedures similar to visual approaches can be employed in any type of weather.

In addition to providing maneuvering capability in bad weather, a TSD can increase spacing accuracy and decrease response time in emergency conditions by making the pilot an active participant in the control process. Such improvements to performance can result in further increases of capacity through modification of existing separation standards. Longitudinal separations for arrival aircraft can be reduced to values which are dependent only on wake turbulence or runway occupancy constraints. Operations on closely spaced parallel runways can be conducted at reduced runway centerline displacements. Departure/Arrival separations can be decreased because the volume and protection time for missed approach airspace can be reduced.

A TSD provides data to the pilot which can enable operations to be efficiently conducted on intersecting runways in any type of weather.

It appears important to provide TSD coverage at low altitudes and on the airport surface. This can be accomplished by extension of present surveillance capability. Many spacing constraints depend on confirmation that a runway is clear and that a runway crossing conflict will not occur. If appropriate TSD coverage could be provided at low altitudes and on the surface of the airport, aircraft could be monitored during takeoff, landing, and taxi. Unusual situations such as runway blockage due to a blown tire or a missed exit could be spotted sooner and would be less critical from a control standpoint. Further reduction of separations which are based on runway occupancy constraints could be possible.

5.3 Recommendations for Further Study

The test program discussed in this thesis was designed to survey the potential uses and benefits of a TSD. No attempt was made to examine any particular phase of TSD operations in detail. Further simulation, analysis, and flight tests will be necessary to adequately examine many of the preliminary findings which are presented in this report. Particular attention should be devoted in future research to developing and using quantative measures for many of the parameters which could only be treated qualitatively in this initial experimental program.

Three areas which appear most promising for further research are:

1. Investigation of a TSD's contribution to safety and pilot assurance.
2. Evaluation of a TSD as a collision avoidance or proximity warning device.
3. Further investigation of ATC procedural changes based on use of a TSD for terminal area maneuvering.

Attempts should be made to devise measures with which a TSD could be evaluated in normal operations, ATC abnormal situations, and subject aircraft emergency conditions in both the NAS/ARTS and future ATC system environments.

The test program did not directly address the collision avoidance problem. Experiments which consider maneuvering capability and pilot reactions in potential collision situations which involve 2, 3, or more aircraft should be tested at the earliest opportunity. Included should be consideration of cooperative, neutral, and misreacting targets, pop-up traffic, and mixed speed traffic in two and three avoidance dimensions. Interesting measures for such cases might be:

1. Threat detection time
2. Miss distance
3. Maneuvering load factor
4. Maximum pitch, bank, altitude and heading excursion.

Care should be taken to observe any failures to identify a potential collision or tendencies to misreact.

Efforts should be made to extend the ATC procedural tests which were considered in cases 4 through 10 to include a wider variety of operating conditions. Tests can be performed with multi-aircraft situations in which targets actively respond to, and interact with, subject aircraft maneuvers. New cases should be tested which involve parallel runway, intersecting runway, and departure operations. Cost-effectiveness studies regarding improvements in ATC efficiency and increases of capacity must be performed.

Provision is needed for operation of the simulated aircraft in various flight control configurations. Alternative autopilot, approach coupler, flight director as well as manual modes should be available to the pilot for proper task evaluation. The effect of the level of air turbulence on task performance needs to be explored.

A wide range of other questions regarding development of TSD's can be considered. Definition of the role which TSD's will play in V/STOL or military systems, consideration of reduced cost equipment for low performance aircraft, and data link frequency allocation are among the critical issues which must be addressed in early stages of development. Examination of the changes which must be made in Federal Aviation Regulations, airspace designation, ATC procedures, and a host of other problems can provide topics for interesting and fruitful research.

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