GENERAL AVIATION SINGLE PILOT IFR AUTOPILOT STUDY

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SUMMARY

Five levels of autopilot complexity were flown in a single engine IFR simulation for several different IFR terminal operations. A comparison was made of the five levels of complexity ranging from no-autopilot to a fully coupled lateral and vertical guidance mode to determine the relative benefits vs. complexity/cost of state-of-the-art autopilot capability in the IFR terminal area. Of the five levels tested, the heading select mode made the largest relative difference in decreasing workload and simplifying the approach task. It was also found that the largest number of blunders was detected with the most highly automated mode. The data also showed that, regardless of the autopilot mode, performance during an IFR approach was highly dependent on the type of approach being flown. These results indicate that automation can be useful when making IFR approaches in a high workload environment, but also that some disturbing trends are associated with some of the higher levels of automation found in state-of-the-art autopilots.

INTRODUCTION

General aviation IFR operations have been increasing rapidly in the past few years. This increase is expected to continue and estimates are that the number of operations will double within the next 10 years. Along with this increasing IFR activity is a corresponding increase in accidents.[1]

A review of incident and accident data during IFR flights[1,2] shows several areas where incidents and/or accidents are most likely to occur. IFR flight in the terminal area, for example, during approach and landing, is usually associated with one of the highest incident and accident rates in single pilot IFR operations.[1-4] In many of these cases it appears that some level of automation might help reduce pilot workload and increase the safety of the flight. General aviation pilots, especially those flying single engine aircraft, however, have frequently resisted purchasing an autopilot for many reasons, (complexity/cost, reliability, pilot acceptance, etc). It is suggested that a simple low-cost partial capability autopilot can frequently provide sufficient benefits in an IFR environment to justify its use, whereas, a complete highly automated autopilot may be undesirable or unaffordable. This study compares relative benefits versus complexity/cost of state-of-the-art autopilot capability in the IFR terminal area.

The paper reports on research comparing various levels of autopilot complexity flown in a single engine IFR simulation for several different IFR approaches. The analysis reported in the paper represents an overview of the results. Examples are presented to illustrate some of the conclusions.

ABBREVIATIONS

ADF	automatic direction finder
BC	back course
CDI	course deviation indicator
COM	communication
DG	directional gyro
DH	decision height
GS	glideslope
HAC	heading select with lateral nav coupler and altitude hold with vertical nav coupler
HC	heading select with lateral nav coupler
HS	heading select
IFR	instrument flight rules
ILS	instrument landing system
K	kilometers
LOC	localizer
N	nautical
NA	no-autopilot
NAV	navigation
NDB	nondirectional radio beacon
OBS	omni bearing selector
PIO	pilot induced oscillation
VOR	very high frequency omni range
WL	wing leveler
WX	weather

Simulation Facility

The tests were performed on the NASA Langley general aviation simulator. The simulator, flown in the fixed-base mode, was configured and programmed as a typical high wing single engine aircraft. Figure 1 shows an outside view of the simulator. The cockpit was outfitted with typical basic aircraft instruments. In addition to these instruments, the following were also included: an ADF receiver, two NAV COM systems with corresponding CDI's, and a complex autopilot system. Figure 2 shows an inside view of the cockpit. The simulation also incorporated a video out-the-window visual presentation, a programmed navigational area encompassing the landing approaches flown, a realistic engine and airstream noise system, and a force feel wheel and column control loader.

The visual out-the-window scene was used for breakout and landing, weather permitting. The scene is a video presentation of a map model that encompassed a scaled area of approximately 4.4 km (2.4 N miles) by 13.9 km (7.5 N miles).[5] Although two airports were located in the scene, all approaches were set up for only one of the airports. However, the second airport did play an unplanned part in some of the tests. This will be discussed later. Landing and taxiing can be accomplished with this visual presentation.

The programmed navigation area on the computer encompassed the five airports used in this study. All the programmed NAV facilities duplicated the local real-world NAV environment. All radio aids, magnetic variation, etc, were included in the simulation. The simulation did not, however, include some of the anomalies associated with the specific real world NAV installation (i.e., scalloping, multiple glideslope paths, etc).

Method

Five levels of autopilot automation were tested. The five, in order of increasing levels of automation, consisted of: (1) no-autopilot (NA); the basic aircraft, (2) wing leveler (WL); the WL mode used in this study did not have a centering detent on the roll command knob, (3) heading select (HS); a course selector directional gyro was used in this mode, (4) heading select with lateral NAV coupler (HC); this mode included lateral guidance for both VOR and ILS navigation, and (5) heading select with lateral NAV coupler and altitude hold with vertical NAV coupler (HAC); in addition to the previously discussed capabilities this mode also included a choice of pitch attitude hold, altitude hold, or vertical NAV guidance (i.e., glideslope coupler).

Five airports and their associated radio NAV aids located in the general vicinity of Langley Research Center were programmed and used in this study. The types of approaches included two ILS approaches, one VOR approach, one LOC BC approach, and one NDB approach. These approaches, and other pertinent information, are given in more detail in table I.

The ceiling and visibility for each data run were randomly chosen from three conditions predefined for each of the five approaches. They were: (1) 15.2 m (50 ft) ceiling and 0.8-km (0.5-mi) minimums for the given approach, (2) published minimums for the given approach, or (3) 61 m (200 ft) above ceiling and double visibility of published minimums for the given approach. All the runs were flown in moderate turbulence (1.2 m/sec (4 ft/sec)) and 20 kt winds from a predefined direction. (See table I.)

Seven subjects were used in the tests: Two NASA test pilots and five IFR rated pilots with various levels of IFR and autopilot experience. Each subject flew a total of 27 data runs. This included the 25 different combinations of five autopilot modes and five different approaches. The extra two runs per subject were repeats for replication purposes. The order or presentation was randomly determined for each pilot. Simulation sessions were scheduled for 2-1/2 hours with a 15-minute break halfway through the session. Except for one subject, no two sessions were on the same day. Four to five sessions were usually required to complete one pilot's set of runs.

Prior to making any data runs, the subjects were scheduled for a session during which they were able to practice all autopilot modes until they were satisfied with their performance with the autopilot. The approaches used for data (table I) were not used in the practice sessions.

TABLE I.- APPROACHES

Airport	Runway	Approaches	Display	Wind
Norfolk, VA	5	ILS	CDI	091°/20 kt
Atlanta, GA	8	ILS	CDI	225°/20 kt
Newport News, VA	25	LOC/BC (Holding)	CDI	290°/20 kt
Franklin, VA	9	VOR	CDI	332°/20 kt
Wakefield, VA	20	NDB	Fixed compass card	155°/20 kt

Data Acquisition

The piloting task consisted of flying the specified approach (table I), making the required pilot reports, and performing a side task. The pilot reports were specified for the particular approach being flown. The side task was a self-pacing velocity/distance/time problem solved by using a hand held E6B type flight computer. For the side task, the subject would, upon his request, be given a problem. He would solve the problem, when time was available, and report the answer. The radio communication system in the simulator was used for this process. The subject was told to perform the side task only when it would not interfere with or change the quality of the approach being flown. The problems and answers for each run were recorded.

The pilots were given handouts which included all five approach charts, their aircraft location, the initial conditions for each approach, and the required reporting points. Table II shows typical initial conditions for one of the approaches.

TABLE II.- INITIAL CONDITIONS

Newport News LOC BC Rwy 25	
Altitude	61 m (2000 ft)
Heading	065 deg
Airspeed	100 kts
Wind velocity*	20 kts
Wind direction	290 deg

*From 305 m (1000 ft) to ground wind velocity goes from 20 kts to 10 kts.

TABLE II.- INITIAL CONDITIONS (cont'd)

Newport News LOC BC Rwy 25	
Turbulence	moderate (1.2 m/sec (4 ft/sec))
WX conditions	day time/ceiling and visibility as specified
Flaps	0
NAV1	110.1 mc
OBS 1	--
NAV 2	116.9 mc
OBS 2	342 deg
ADF	375 kc

NOTE: Use tear drop entry

The initial conditions positioned the aircraft at a location where a final approach and landing clearance would typically be received for that approach.

At the beginning of each day's session, the subject was given a practice run. Also, prior to each data run, the subjects were given sufficient time to review the approach chart, conditions, and procedures. They were then given an IFR clearance and reporting points for the approach and the simulation was started. The runs were ended after landing and rollout or 10 to 20 seconds after initiation of the missed approach.

The data taken during each approach consisted of flight technical error, ground track and profile plots, pilot workload rating and comments, and side task results.

RESULTS AND DISCUSSION

A review of the data disclosed several events and trends associated with pilot performance in flying the various autopilot modes. The following analysis is based on pilot comments, pilot ratings, side task results, and ground track and profile plots. In analyzing the data, it is necessary to consider the interrelationship of several of the above data to fully understand the results. Results from a single source of data can often be misleading. For example, the side task results are dependent not only on task difficulty but also on total time required to complete the approach, whereas the time required to complete the approach is dependent on the specific approach being flown, piloting technique in flying the approach, and the difficulty of the approach. Also, the total time to fly the approach may be either longer or shorter if the pilot blunders or deviates from the normal approach path.

The following discussion includes a brief comparison of the five levels of autopilot complexity. This is followed by a discussion of the effects of the different approaches. Finally, an indepth discussion of trends, as related to the various levels of automation, is presented.

Autopilot Comparison

Side Tasks.- The side task results, figure 3, in general are representative of all the data. This figure shows the average number of problems completed per run during all the approaches for all the subjects at each level of autopilot complexity. The upper and lower limit bars represent the maximum and minimum of the averages of the individual subjects at each level of autopilot complexity. Implicit in using a secondary task is the assumption that the more difficult the task, the fewer problems completed, hence, the higher the workload associated with the primary task. As can be seen by the data, the workload tends to decrease (increased secondary task performance) as automation level is increased. Significant, however, is the leveling off of the workload for automation levels greater than the HS mode. One interpretation of this phenomenon is that beyond the HS mode the subject trades off the workload associated with flying the control task for the workload required to monitor the autopilot's control of the flight task. This results in little net difference in primary task workload beyond the HS mode.

Pilot Workload Ratings.- Figure 4 shows a similar relationship with respect to subjective pilot workload ratings. At the end of each run the subject rated the primary task on a workload scale of 1 to 7 with 1 designated as the easiest and 7 as the hardest. It should be realized that this type of rating technique typically produces a relative workload rating of difficulty rather than an absolute workload rating. The format of figure 4 is similar to that of figure 3, i.e., figure 4 shows the average workload rating per run during all the approaches for all the subjects at each level of autopilot complexity. The upper and lower limit bars represent the maximum and minimum of the averages of the individual subjects at each level of autopilot complexity. These results tend to agree with the side task results, i.e., increased automation decreases workload. There is also a slight leveling off of the workload beyond the HS mode, but it is not as dramatic as in the side task data.

Ground Track Plots.- Figures 5, 6, and 7 show typical pilot control of flight ground tracks. The three ground track plots shown are for the NA, WL, and HS autopilot modes. All are for the Atlanta ILS approach and were all flown by the same subject. An altitude profile plot is also included in figure 5. These figures illustrate the differences in the frequency characteristics. The NA mode, figure 5 for example, exhibits two frequencies; a high frequency with low damping and a low frequency. As the level of automation increases, see figures 6 and 7, the high frequency component decreases, in both amplitude and frequency. This results in an apparent smoothing of the ground track trace. This smoothing trend with automation was characteristic for all the different approaches flown in this study.

No-autopilot (NA) Mode.- In the NA mode the pilot flew the basic aircraft without assistance from any autopilot mode. The data, including pilot comments and ratings, show this mode to be the most difficult to fly. Typically, the biggest problem in flying the NA mode was high workload (as measured by the side task and pilot ratings) and less precise flying. Figure 8 shows an example of this characteristic for the Newport News LOC BC approach. The holding pattern during this run does not conform to a typical pattern. Also, the ground track of the NA mode exhibits relatively high frequency and low damping characteristics.

Wing Leveler (WL) Mode.- This mode was slightly easier than the no-autopilot mode, but some characteristics of the mode were disconcerting. Many of the subjects found the WL inputs disturbing when trying to control pitch. The control wheel moving in roll interfered with pitch inputs. Also, the particular autopilot used in this study did not incorporate a centering detent on the roll command knob. This lack of accurate centering frequently resulted in the aircraft being in a slight bank with the pilot having to continually make inputs to keep wings level. A centering detent is considered very desirable, especially when flying in turbulence. An interesting side issue is that those subjects not intimately familiar with the WL mode commented that it took considerable practice to become comfortable with this mode. Even considering all the above, however, all pilots preferred this mode to the no-autopilot mode.

Heading Select (HS) Mode.- The HS mode was considered, by the subjects, to be much easier to fly than the WL mode. Of the five levels of autopilot complexity tested, the HS mode was found to make the largest difference in decreasing workload and simplifying the approach task. It was also observed that the workload, as measured by the side task, leveled off for the HS, HC, and HAC modes (see figure 3).

Heading Select with Lateral NAV Coupling (HC) Mode.- The next level of complexity, the HC mode, was considered somewhat easier than the HS mode but not by a large margin. One interesting point, however, is that in this mode no comments were made about roll inputs interfering with the pilot's control of pitch. These comments were made in the WL and, to a lesser degree, the HS modes. These may be due to the fewer inputs required in these two latter modes.

Heading Select with Lateral NAV Coupling and Altitude Hold with Vertical NAV Coupling (HAC) Mode.- The most fully automated mode tested, HAC, as expected, was somewhat easier to fly than the HC mode, but again not by a large margin over the HC mode. In addition, several problems associated with the HAC mode, especially in a high pilot workload environment, became apparent. To a lesser degree some of these problems also existed for the HC mode. This will be discussed later.

Approaches

In addition to the varying levels of difficulty in flying the approach task due to a given level of autopilot automation, the different types of approaches were also found to be a factor in difficulty of flying the task. This was taken into consideration in analyzing and comparing the autopilot data. In general, the data show that the ILS approach (LOC and GS) was the easiest to fly. The ILS data included the runs from both the Norfolk and Atlanta approaches.

The Newport News LOC BC and Franklin VOR approaches were about the same in overall task difficulty. They were, however, more difficult than the ILS approach. Some variability did exist for the two approaches from pilot to pilot and from autopilot mode to autopilot mode. It is difficult to make a point to point direct comparison of the two approaches due to the difference in display sensitivity, the mental gymnastics of reverse sensing, and the added task of holding in the LOC BC approach.

The Wakefield NDB approach was found to be the most difficult by the majority of the subjects. This is partly due to the different display used in this approach, i.e., the typical ADF relative bearing needle on a fixed compass card. This lack of a computed, displayed error for the desired path makes the tracking task more difficult. The pilot must continually compute error information mentally, using the relative bearing and DG information. The differences in difficulty in flying the various approaches can, to a large degree, be related to differences in display format, information, and sensitivity and to procedures.

General Trends

Several disturbing trends were noted as the level of autopilot automation was increased. In general, an increased level of automation tends to take the pilot out of the aircraft control loop. He becomes a manager of the autopilot functions. The effects of this change in duty appear to be emphasized in the HAC mode. The subjects were more likely to lose track of where they were in the approach. It seemed that in monitoring the autopilot they would associate instrument readings with the autopilot functions rather than to situational awareness. Therefore, if the autopilot functions were either set incorrectly or interpreted incorrectly, the subject would frequently perform the wrong task, thinking that everything was normal. This would frequently lead to an incident or blunder. An example is shown in figure 9 (Franklin VOR approach, HAC mode). The run began with the autopilot set in the heading select mode. After crossing the VOR, a right turn to the outbound course was initiated. At this point the autopilot was switched to omni coupler to intercept and track the outbound course. However, the subject had neglected to reset the correct bearing on the CDI. Therefore, the autopilot reintercepted and tracked the original bearing of the CDI. Eventually, he realized his mistake and set the correct outbound bearing. The aircraft then took up a 45° intercept path to the new bearing. After a fair amount of time he still had not intercepted the outbound course but due to the time into the approach he decided to make a pseudo procedure turn using heading select. At this point in time he also set in the correct inbound heading on the CDI. Upon completion of the procedure turn he continued in heading select until the CDI needle came alive. He than selected omni coupler and completed the approach without further incident. It is likely this incident would not have been detected in the real world.

Another subject (figure 10, Wakefield NDB approach, HAC mode) made his final let down on an outbound heading. He leveled off and made his missed approach without ever realizing his mistake. Another interesting facet related to this run is the fact that the NDB at Wakefield is located on the airport. The missed approach should have been executed when, if in this case, the NDB was crossed. In fact several, otherwise normal, runs were also flown at Wakefield in which the missed approach was executed prior to crossing the NDB inbound. It seems that the subjects would time their outbound leg and use this time, rather than the NDB crossing, to execute their missed approach. The 45^{o} left headwind on the inbound heading was obviously a contributing factor in these incidents. This situation implies a lack of positional awareness.

Several other comments about the HAC mode are considered relevant at this point. A couple of subjects commented that, while flying the HAC mode, they had a tendency, at times, to forget to perform the side task. Another subject felt that the altitude hold and glideslope coupler could create a safety issue. The pilot can be lulled into a false sense of security or complacency with all the automatic features. The problem appears to be almost as if the pilot thinks of the autopilot as a copilot and expects it to think for itself. He allows himself to become completely engrossed in other tasks once the autopilot is set. Hence, he is frequently late in resetting new functions or he may become confused as to exactly where he is in the approach and not reset all the necessary functions or controls. Still another subject commented that the more automated his autopilot the less he trusted it. He stated he had trained himself to expect and look for problems of an insidious nature when using complex autopilots.

The above comments agreed with the relationship of blunders versus autopilot automation. The HAC mode encompassed the largest number of detectable blunders.

Remember also that the type of approach was a factor on the prevalence of incidents or blunders, the fewest exhibited during the ILS approaches and the most during the NDB approach. One notable exception was during an Atlanta ILS approach where the subject got into a PIO at the middle marker and impacted the ground. (The PIO characteristic of ILS sensitivities associated with the middle marker has been observed in independent work at NASA LaRC.) The no-autopilot mode was being used for this run. The DH for the approach was 61 m (200 ft) above the ground. However, this was only one of two blunders for the more than 70 ILS runs flown. The second was when the subject executed a missed approach at the outer marker thinking he was at the middle marker. The altitude at the outer marker was 853.4 m (2800 ft), whereas at the middle marker it would have been 365.8 m (1200 ft). This latter run was flown with the HAC mode.

Several other incidents or blunders not related directly to the autopilot mode are worth mentioning at this point. One subject executed his missed approach early for three of the five runs he flew on the Newport News LOC BC approach. The wind for this approach was a 45° right headwind to final approach. The subject stated that he intentionally does not use reported winds in his missed approach timing. Another problem in LOC BC approach was positional disorientation due to reverse sensing on the CDI. One subject became so confused he became lost on one run and had to abort.

The Franklin VOR approach demonstrated similar problems. In several runs, for example, the subjects overshot the outbound heading on the approach course by a fairly large margin. Also, the procedure turn was, on several occasions, considerably larger and out of porportion to the desired path. The approach had a 20 knot, 45° tail wind relative to the final approach heading. This tail wind apparently also caused a larger number of missed approaches. The subjects would not compensate for the tail wind in their approach timing, would descend too slow, and breakout beyond the airport.

During the Wakefield NDB approach two subjects landed at a second airport which just happened to be part of visual model. The second airport was located approximately 4.8 km (3 mi) from the destination airport at about 0.8 km (0.5 mi) to the left side of the desired approach path. Figure 11 shows the ground track and profile plots of one of these runs. The location of a second airport in the vicinity of the destination airport was not planned as part of the experiment. Therefore, the subjects were not previously told about the location of the second airport. This incident, having occurred, however, emphasizes the problem associated with airports located in the vicinity of each other.

CONCLUDING REMARKS

A total of 189 IFR approaches were flown on the NASA Langley general aviation simulator to compare various levels of automation of autopilot systems. Seven IFR rated pilots flew five different airport/approaches with five levels of autopilot complexity.

Of the five levels of autopilot complexity tested, the subjects rated each level of added automation to be somewhat easier to fly than the previous level, except for one mode. This mode, heading select, was considered to be much easier than its next lower level of automation. Also, the data show that the heading select mode made the largest difference in decreasing workload and simplifying the approach task. The most fully automated mode, which included altitude hold and vertical nav coupling, exhibited some disturbing aspects, i.e., the largest number of blunders was detected with this mode. Also, the side task results showed no decrease in workload from its next lower level of automation.

The data show that the overall quality of performance during an approach was highly dependent on the type of approach being flown. The ILS approach, localizer, and glideslope were found to be the least difficult. The VOR and localizer back course approaches were rated about the same in difficulty, but were considered more difficult than the ILS approach. The NDB approach was considered to be the most difficult of those tested.

The results of this study indicate that automation is desirable when making IFR approaches in a high workload environment, but also that some disturbing trends are associated with the higher levels of automation as presently implemented in state-of-the-art autopilots. It is believed however, that a better man/machine interface could alleviate these problems. The data further suggest that the heading select mode may currently be the best choice for the IFR approach task when considering both benefits and costs.

REFERENCES

1. Forsyth, Donna L.; and Shaughnessy, John D.: Single Pilot IFR Operating Problems Determined from Accident Data Analysis. NASA TM-78773, September 1978.

2. Bergeron, Hugh P.: Analysis of General Aviation Single Pilot IFR Incident Data Obtained from the NASA Aviation Safety Reporting System. NASA TM-80206, October 1980.

3. Ames Research Center and ASRS Office: NASA Aviation Safety Reporting System: Second Quarterly Report. July 15 - October 14, 1976. NASA TM X-3494, December 1976.

4. Ames Research Center and ASRS Office: NASA Aviation Safety Reporting System: Third Quarterly Report. October 15, 1976 - January 14, 1977. NASA TM X-3456, May 1977.

5. Rollins, John D.: Description and Performance of the Langley Visual Landing Display System. NASA TM-78742, August 1978.

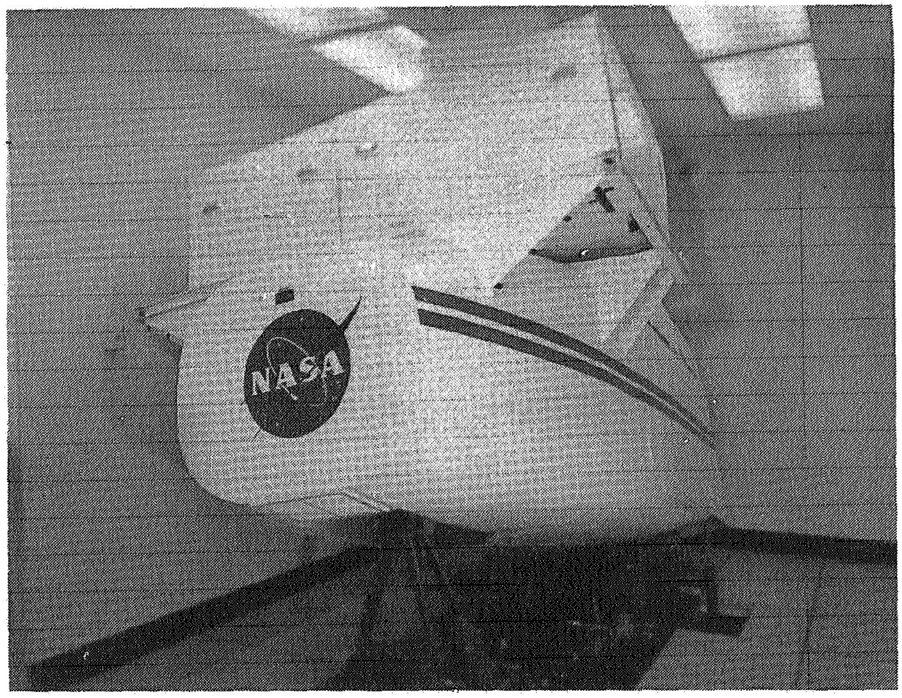

Figure 1.- Outside view of simulator.

Figure 2.- Inside view of simulator.

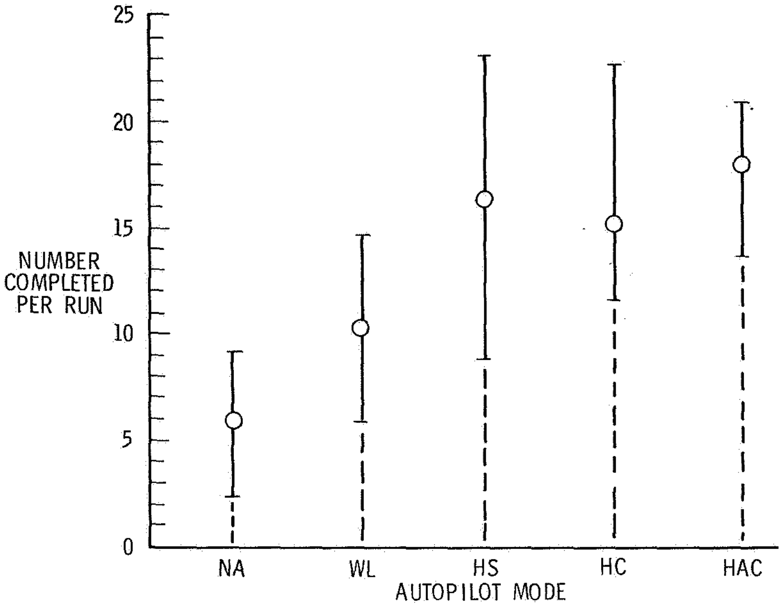

Figure 3.- Average number of side tasks.

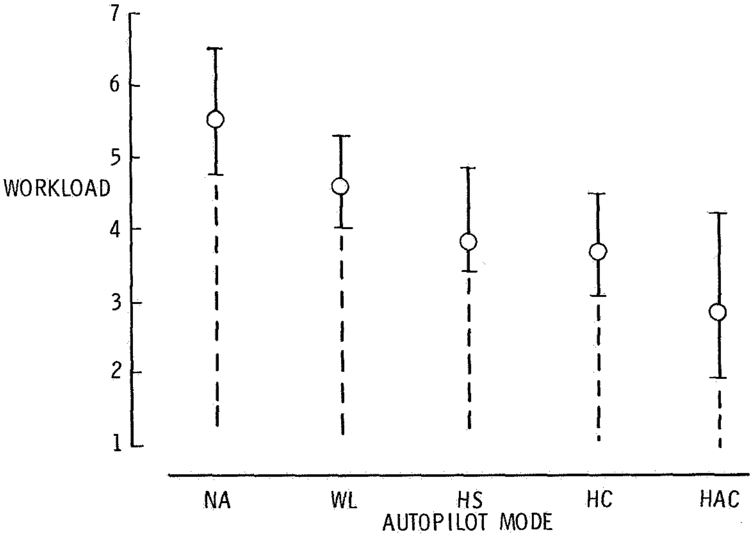

Figure 4.- Workload ratings.

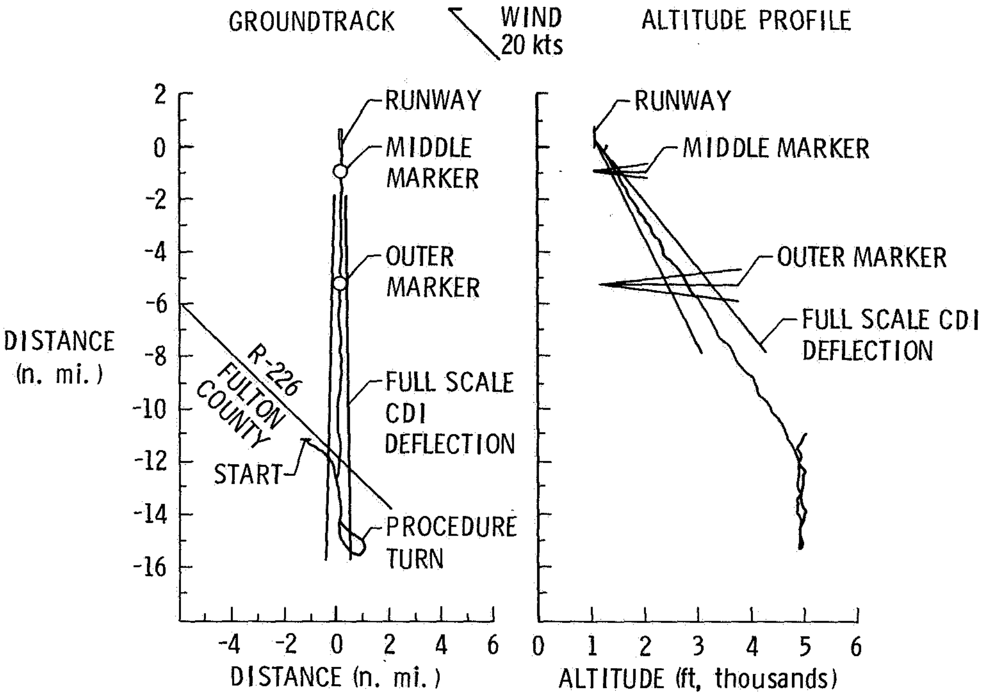

Figure 5.- Atlanta ILS appraoch. No-autopilot mode. (Note: 1 ft = 0.3048 m.)

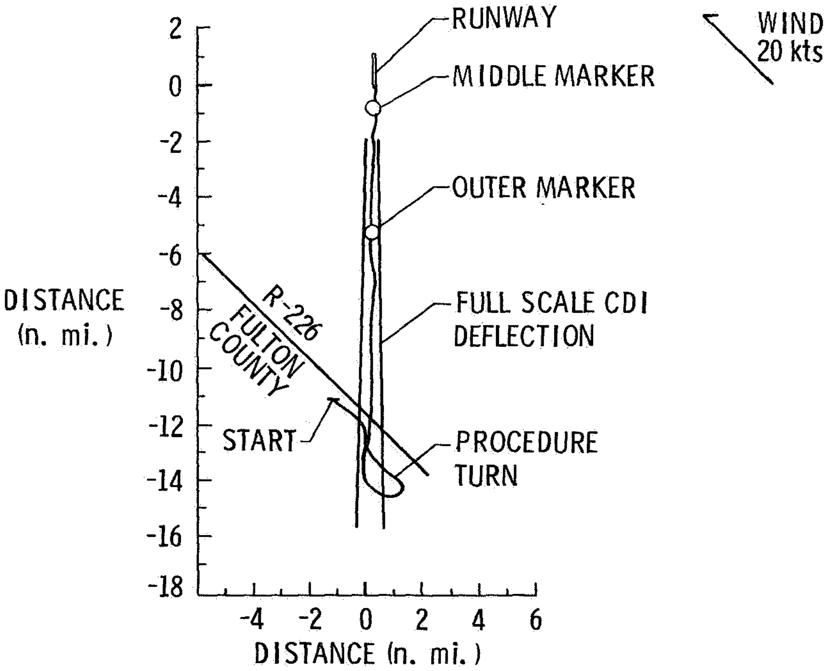

Figure 6.- Groundtrack Atlanta ILS approach. WL autopilot mode.

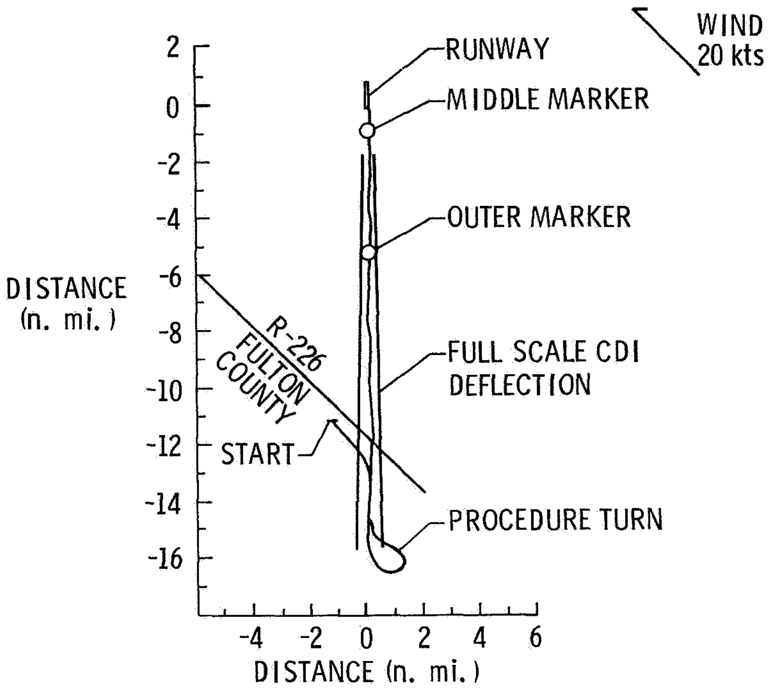

Figure 7.- Groundtrack Atlanta ILS approach. HS autopilot mode.

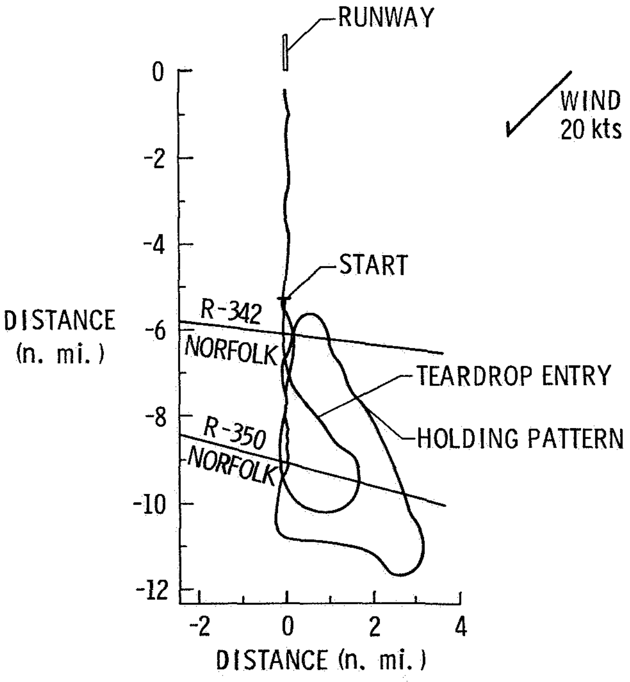

Figure 8.- Groundtrack Newport News LOC BC approach. No-autopilot mode.

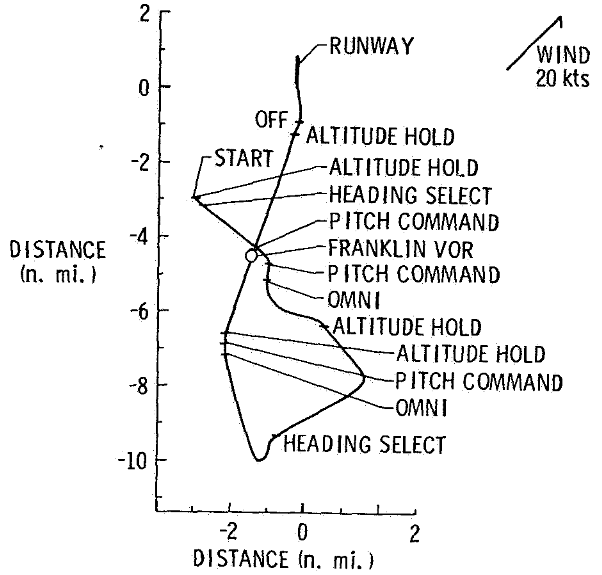

Figure 9.- Groundtrack Franklin VOR approach. HAC autopilot mode.

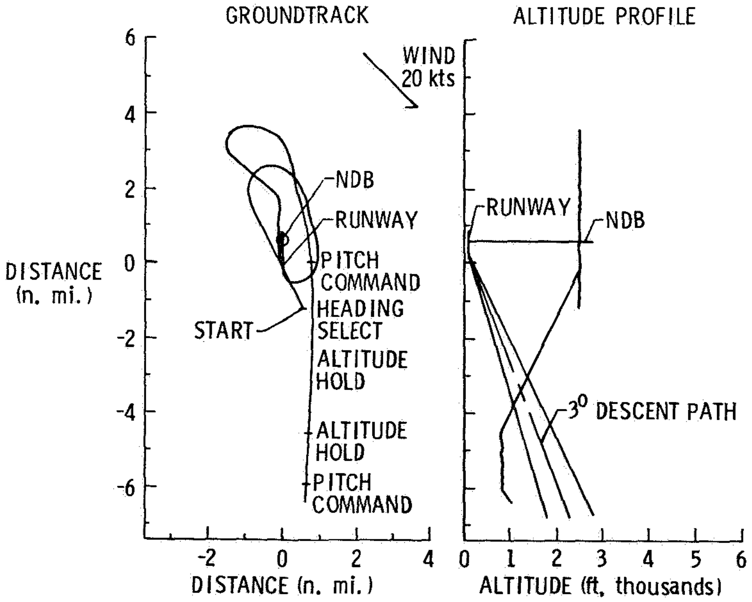

Figure 10.- Wakefield NDB approach. HAC autopilot mode.
(Note: 1 ft = 0.3048 m.)

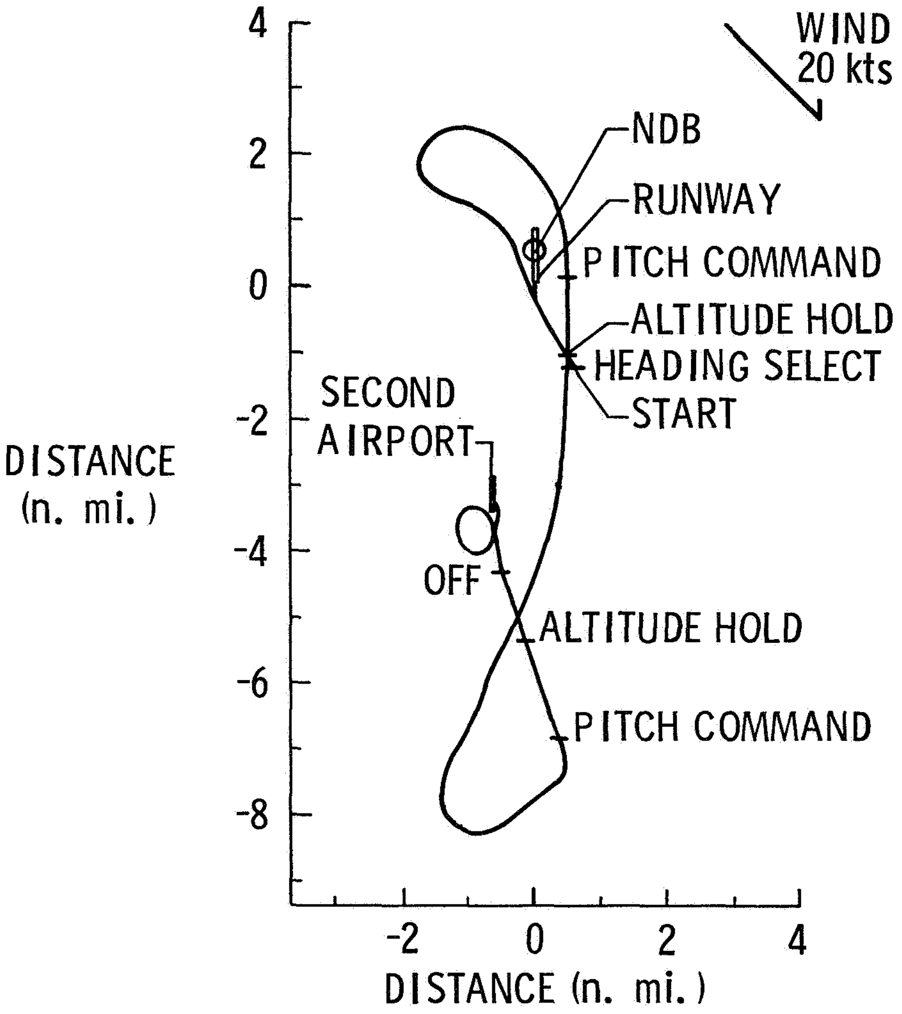

Figure 11.- Groundtrack Wakefield NDB approach. HAC autopilot mode.