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EXPERIMENTAL STUDY OF ACOUSTIC DISPLAYS OF FLIGHT PARAMETERS IN A SIMULATED AEROSPACE VEHICLE

by Darryl Katz, Jerry A. Emery, Richard F. Gabriel,
and Alan A. Burrows

Prepared by
DOUGLAS AIRCRAFT COMPANY, INC.
Long Beach, Calif.
for Flight Research Center

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EXPERIMENTAL STUDY OF ACOUSTIC DISPLAYS OF FLIGHT PARAMETERS IN A SIMULATED AEROSPACE VEHICLE

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SUMMARY

The research reported herein was addressed to evaluation of the feasibility of employing acoustic stimuli in the presentation of information to humans. The considerations responsible for interest in the acoustic display concept include potential alleviation of visual loading of pilots, increased flexibility of displays, and improved information processing capability achieved through the use of more than one sense modality. In particular, applications of acoustic displays of target location in target detection and of flight parameters in aerospace vehicles were experimentally examined in the program described below.

A simulated target detection task was devised and provisions were made for displaying the lateral location of simulated targets acoustically by means of an interupted 500 cycle/second tone emanating from the direction of the target. The same information could be displayed visually on a meter or simultaneously by the acoustic display and the visual display (meter). Subjects engaged in the target detection task, which required location and identification of targets, while concurrently involved in a visual tracking task. A secondary acoustic task was superimposed during some trials and, in all cases, the performance of subjects was evaluated as a function of the type of target location display.

With respect to all measures of target detection performance taken, the visual display of target location was inferior. These differences were highly statistically significant for several of the performance measures. There were not significant differences in performance on the secondary visual and acoustic tasks as a function of display condition. Performance on these tasks, however, was better, on the average, under acoustic and acoustic/visual display conditions for most measures.

A major phase of the program was devoted to the development of acoustic displays of flight parameters for experimental evaluation. This portion of the effort included a literature search, logical considerations, and several experimental phases. The primary results included:

1. A one-channel acoustic display of roll angle (ϕ). Roll angles commanded by means of a "binaural" loudness cue wherein the pilot was commanded to roll toward the side corresponding to the the louder signal. The magnitude of the loudness difference was related to the error magnitude.

2. A two-channel acoustic display in which the display described in 1 above was combined with an acoustic angle of attack(α) command. "Increase angle of attack" was commanded by square wave modulation of the frequency of the acoustic signal at 10 cycles/second. "Decrease angle of attack" was commanded by sinusoidal modulation of the frequency of the signal at 4 cycles/second. In both cases, the magnitude of the modulation was related to error magnitude.

3. Visual command displays of roll angle and angle of attack. These were used as control displays in that they provide the same information as the acoustic displays described above and differ from them primarily in sense mode. The conventional visual displays of roll angle and angle of attack differ from the acoustic displays in both sense mode and in type of information displayed (command vs. situational).

In the final phase of the program, the acoustic displays and command visual displays described above were experimentally evaluated under simulated X-15 flight. The conventional visual display and the acoustic displays driven by "augmented" error signals[1] were included in the evaluation. For this purpose, a simulator was constructed which had flight dynamics based on those of the X-15 and pilot-subjects flew simulated altitude missions under the various display conditions. Performance measures taken include the following:

1. Integral of absolute error in roll angle and in angle of attack during various portions of the mission profile.

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[1] "Augmented" error signals were a function of the error and its, 1st and 2nd derivatives with respect to time. The function was linear and the coefficients were determined empirically for best performance.

2. Absolute error in peak altitude and in re-entry angle of attack.

3. Performance on a concurrent verbal comprehension task.

Subjective reactions of the subjects were also obtained concerning the displays, the experiment, and the general concepts under examination.

In general, performance under acoustic display conditions was as good or better than performance under the conventional visual display condition. In some cases, there were indications in the data of superiority of the command visual displays. There were no consistent indications of advantages related to "augmentation" of the acoustic displays but, given the lack of statistical significance and general support of the concept in the literature, "augmentation" was not excluded from consideration as a potentially useful concept in displays.

INTRODUCTION

ACOUSTIC DISPLAYS

The feasibility of employing acoustic stimuli in the presentation of information to humans is supported by numerous sources of data. These include experimental data related to human sensory processes and information processing capabilities. In addition, physical properties of acoustic stimuli, and available methods of manipulating and generating acoustics stimuli, are compatible with many potential applications. Many of these sources are discussed below.

Several a priori considerations suggest advantages of acoustic or acoustic/visual displays over all visual displays in applied contexts. The use of acoustic stimuli for the display of flight parameters in aerospace vehicles constitutes a salient possibility.

In many flight tasks the operator is required visually to fixate on instruments within the cockpit and on distant outside points. It has been shown (ref. 1) that reaccommodation of the eyes, followed by extraction of simple information, takes a large amount of time, even in young subjects with excellent vision. Such lags can accumulate rapidly, particularly during critical portions of a profile, such as landing. The result is a recognition of the need for "head-up" displays, that is, displays which do not require reaccommodation of the eyes from accommodation at infinity, or orientation of the head and/or the eyes to acquire displayed information. Acoustic displays provide one approach toward the fulfillment of this need.

A high degree of flexibility is inherent in the acoustic mode of display. Scales, for example, can be readily transformed because restraints, such as printed dial faces, are absent. Pre-presentation processing of information, such as "quickening" (ref. 2), is highly compatible with acoustic presentation. It is also the case that numerous acoustic display parameters, such as loudness, can be varied for maximum compatability with individual operators.

Current trends in vehicle development result in increased task-loading of operators. Increased visual-loading constitutes a primary factor. There are indications that information transmission by an operator can be effectively increased through the use of multiple sense modalities in the information channel (ref. 3). Audition is probably the most thoroughly studied sense modality other than vision, and the technology relevant to manipulation of acoustic parameters is relatively highly developed. As a consequence, acoustic displays appear to have potential as a means of alleviating task-loading in display/control systems.

There are additional sources of possible advantage in the acoustic display of information. The introduction of a second sense mode in information presentation may enhance the possibility of sub-tasks becoming "automatic."

That is, if an independent and distinct cue is used to elicit the responses required in a sub-task, these responses may occur as required without significantly contributing to task loading. More generally, increased stimulus response compatibility may prevail, in some tasks, with acoustic stimuli. Acoustic stimuli may also serve an alerting function, in warning displays, without major interference with concurrent visual displays.

An early application of acoustic displays is the Low Frequency Radio Range navigation system. Three acoustic signals are used indicating left of the beam, right of the beam, and on the beam. This system, referred to as the A-N system, was in prominent use for many years.

Some work has been reported which was directly addressed to evaluation of acoustic displays of flight parameters. DeFlorez (ref. 4), in the 1930's, actually flew a Fairchild 22 for over 40 minutes while blindfolded, using acoustic displays. In his display, air apeed was coded by the frequency of the auditory signal and heading was coded by a binaural cue. The binaural cue contained no magnitude information. DeFlorez was definitely able to fly, although marginally, using this display.

Forbes (ref. 5) reports work, including FLYBAR, performed in a more controlled situation than the work of DeFlorez. A three channel acoustic display was evaluated, with inexperienced subjects and pilots, in a Link trainer. Turn, bank, and airspeed were displayed by binaural sweep, pitch variation, and rate of "putting," respectively. The subjects were instructed to maintain a straight course under conditions simulating rough air. Following training, "comparable" performance was observed under the acoustic display condition and under the conventional visual display condition.

The acoustic displays described by Forbes were applicable to maintenance of a straight course but more general application is limited by the small number of absolute judgments that a human can make along the stimulus dimensions used (ref. 6). Different acoustic channels or command (error signal) displays are probably essential if acoustic displays are to be flexible.

An acoustic air speed display was developed and evaluated extensively in a Firefly aircraft of the Royal Air Force Institute of Aviation Medicine (ref. 7). The device proved satisfactory and its use, together with that of subsequently developed acoustic angle of attack displays, was related to a significant decrease in carrier landing accidents (ref. 8) in the British Navy.

In a recent series of studies, acoustic displays of velocity, angle of attack, and altitude were developed and evaluated in simulated carrier deck landings (ref. 9). The audio codes employed were based upon frequency modulation and were employed in command displays. Generally favorable conclusions were drawn concerning the feasibility of acoustic displays. In this research, there was a clear attempt to employ more rigorous and logical methodology than is representative of earlier work on acoustic displays. An experimental display development phase was included in the research and objective performance measures were taken during display evaluation. The application of statistical models in data analysis also represented a major step toward objectivity.

PROGRAM OBJECTIVES AND APPROACH

The research program reported herein was addressed to two major goals:

1. Examination of the feasibility of employing acoustic displays in target detection.
2. Examination of the feasibility of employing acoustic displays of flight parameters in aerospace vehicles.

In view of the magnitude of these goals, the program was divided into several phases. The first phase was non-experimental and consisted of a literature search and preliminary analysis of the problem areas of concern. Initial decisions, based on this first phase, served to limit the program to feasible size. Phase one decisions included restriction of the displays and parameters to be experimentally evaluated, specification of performance measures and tasks to be used, and selection of experimental designs for the remainder of the program.

Three experimental phases were conducted:

1. Experimental evaluation of acoustic displays in target detection.
2. Experimental selection of acoustic displays of flight parameters.
3. Experimental evaluation of acoustic displays of flight parameters.

ACOUSTIC DISPLAYS IN TARGET DETECTION

INTRODUCTION

In numerous current and projected applications, humans are required to locate targets in the external environment. Examples of such applications include location of ground targets while operating an aircraft and location of a satellite during a rendezvous and docking maneuver. A "head-up" display of information relevant to target location is desirable in that such a display can be used concurrently with searching behavior without excessive reorientation of the head and reaccommodation of the eyes. The use of an acoustic display in this context is promising in that, in addition to being a "head up" display, it may alleviate problems of visual overload related to visual displays involved, for example, in vehicle control.

Lateral location of target was selected as the parameter to be displayed in this study as a result of its generality across target detection situations. Lateral location is a significant parameter in detection tasks from ground-, sea-, air-, or space-based systems. This parameter was acoustically displayed by a binaural cue because of the expected compatibility between the "left-right" nature of this cue and of the lateral location parameter.

In particular, the lateral target location was coded in lateral source direction of the auditory signal. A low frequency (500 cps) tone was used, so that binaural loudness and phase differences would provide directional cues and it was interrupted 4 times per second to reduce habituation and increase discriminability of direction (ref. 10).

METHOD

The apparatus used in the target detection experiment is present schematically in Figure 1. Appendix A of this report consists of a detailed description of this apparatus.

The error signal associated with a one-dimensional compensatory visual tracking task was presented on the oscilloscope screen located directly in front of the seat. In the absence of inputs, the error signal varied randomly. Control inputs were made through a control stick located to the right of the seat.

In front of the seat, the subtending 90° of lateral angle at the seat was located a rear projection screen. Background "noise," in the form of a large number of white circles on a black background, were projected on the screen via a slide projector. A second projector was programmed to superimpose a target on the screen in the form of a white circle with a gap at the top, bottom, right, or left. Targets appeared at intervals of from 30 to 90 seconds. They appeared at one of 5 lateral positions and one of 2 vertical positions. Targets were removed after 5 seconds or when the 4-position switch located to the left of the scope was moved, whichever occurred first This switch had 4-positions, enabling the subject to indicate the gap location of targets.

An ammeter was located above the scope and could be used to display lateral location of targets. The acoustic signals used to display lateral location of target locations were produced at loudspeakers positioned above the lateral locations of targets. The same effect could be produced using a stereo headset with a pot to sense lateral head orientation and affect the signal appropriately.

Another 4-position switch was located to the left of the seat. It was used, in some cases, for responding to pre-taped verbal messages broadcast over a loudspeaker located behind the screen.

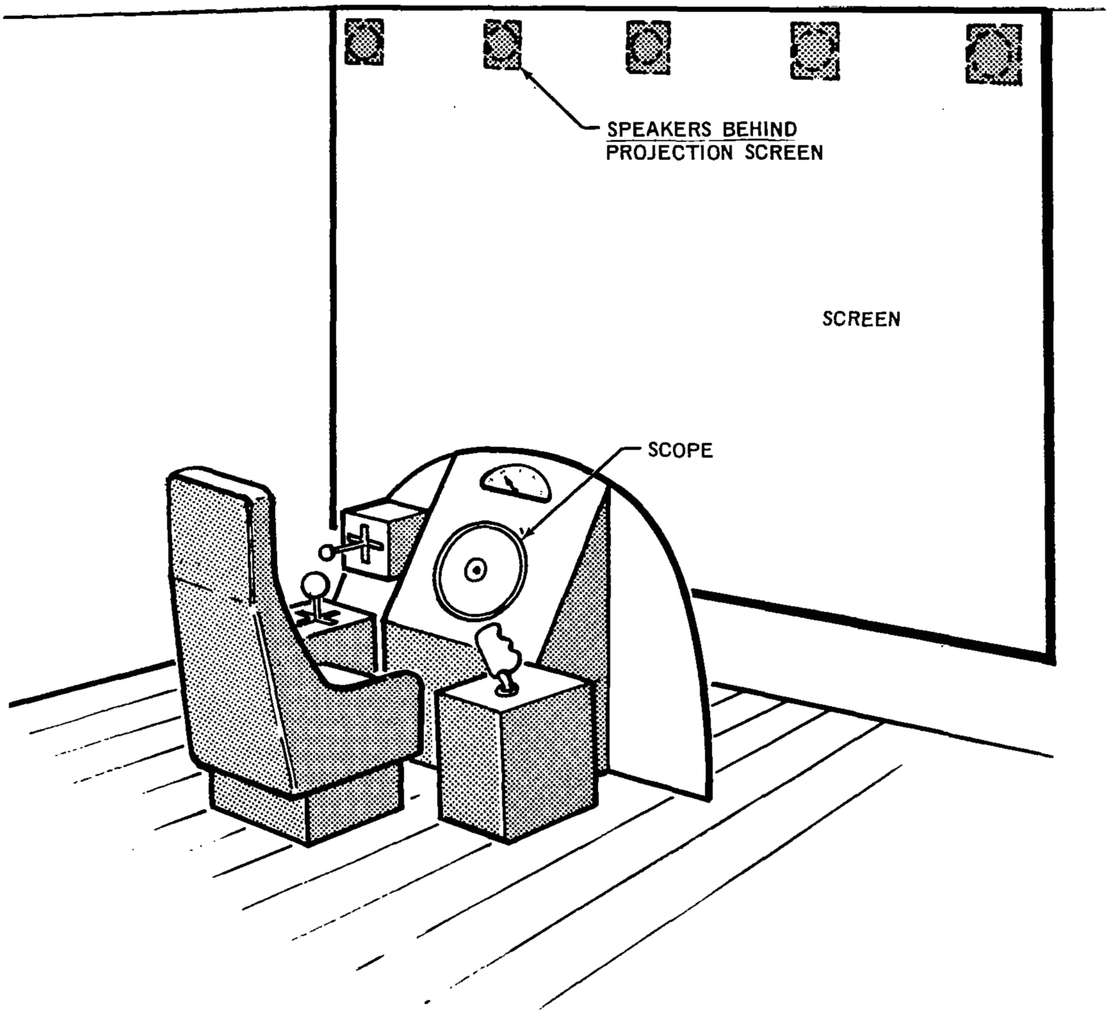

Figure 1: Target Detection Apparatus

Procedure and Experimental Design

Experiment A

Twenty-four undergraduate students from California State College at Long Beach served as subjects in the experiment. All subjects had at least 20/30 corrected vision in each eye and hearing with in 10 db of normal in each ear measured in a standardized hearing test using a Belltone audiometer. The subjects were randomly assigned to 3 groups of 8 subjects each: An audio display group, a visual display group, and an audio/visual (redundant) display group.

Each subject participated during two 20 minute sessions, separated by a 10 minute rest period. During each session, the subject was continuously engaged in the compensatory tracking task. The white "noise" circles were projected on the screen. Every 60 seconds, on the average, a target appeared on the screen and its lateral location was simultaneously displayed (acoustically, visually, or both, depending on which group the subject was in).

Subjects were instructed to minimize error on the compensatory tracking task and to locate targets as rapidly as possible, following their appearance. Location of a target was communicated by indicating the gap location (up, down, right, or left) of the target via the 4-position switch located to the left of the scope. The subject's response removed the target.

Absolute error in tracking was integrated during non-detection time (no target on screen) and, separately, during detection time. Total reaction time (response time) and accuracy in target detection were also measured.

Integral of absolute error data from the compensatory tracking task were analyzed using the factorial analysis of variance design shown in Figure 2 (ref. 11). Reaction time data from target detection were analyzed using the factorial analysis of variance design shown in Figure 3 (ref. 11) and target detection accuracy data were analyzed using a non-parametric test of analysis of variance hypotheses (ref. 12) performed on a data array described in Figure 3.

Data analyses provide for the testing of differences in all measures attributable to individual variables (e. g. Display) and to interaction of variables.

Experiment B

Experiment B was identical to Experiment A, with the following exceptions:

1. Only a visual display group and an audio display group were used.

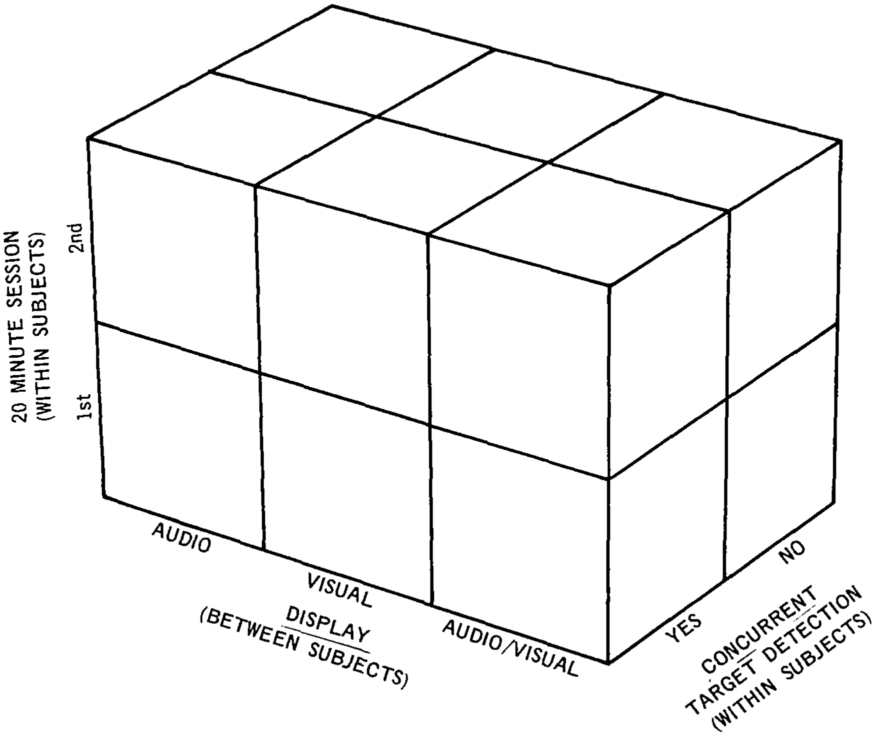

Figure 2: Matrix for Analysis of Tracking Error Data

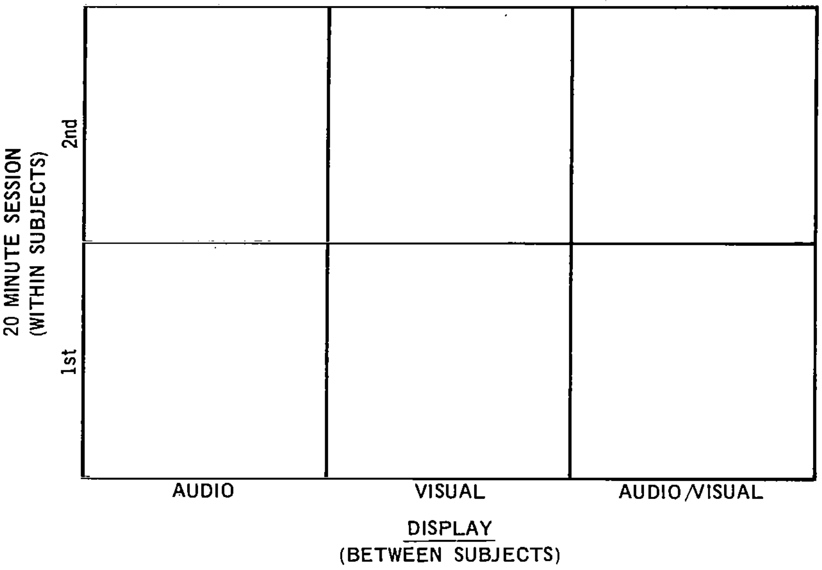

Figure 3: Matrix for Analysis of Target Detection Data

2. There were only 3 subjects in each group.

3. A verbal communications task was added to the detection and tracking tasks. Eight nonsense syllables[2] were selected and presented in random order and with 20 to 40 seconds between syllables. Presentation times were also selected randomly so that prediction was not possible. Four syllables were designated as relevant and required an identifying response on the 4-position switch at the subjects' left. Accuracy and reaction time were recorded.

Matrices for data analyses are identical to those in Experiment A except that the audio/visual display group is eliminated. Accuracy and response time measures from the verbal communication task were analyzed in the same manner as the analagous target detection measures.

RESULTS

Experiment A

Target detection performance with the acoustic and audio/visual display was clearly superior to that obtained with the visual display. The statistically significant effect of target location display on detection accuracy is shown in Table 1a. Table 1b contains the mean performance scores. It is seen that both displays involving the binaural audio cue yield superior performance to the visual display. The same relationships for the response time measure in target detection are shown in Tables 2a and 2b. The Neuman-Kuels test (Table 2c) indicates that the inferiority of the visual display, as reflected in response time, is statistically significant.

Performance on the compensatory visual tracking task, as shown in Table 3, is significantly better on the second run than on the first and significantly better without concurrent target detection than with it, as was clearly expected. Although tracking performance did not differ significantly as a function of display type (Table 3a), it was numerically better, on the average, with the acoustic and audio/visual displays than it was with the visual display, (Table 3b).

Thus, superior performance was observed under the acoustic and audio/visual display conditions, than under the visual display condition, relative to all measures used in Experiment A. These observed differences were in most cases statistically significant.

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[2] A nonsense syllable consists of three letters which do not form a word in which the first and last letters are consonants and the middle letter is a vowel.

TABLE 1

TARGET DETECTION ACCURACY

(NUMBER CORRECT OUT OF 20)

EXPERIMENT A

A. WILSON'S TEST ON SCORES

Source	χ^2	df	(p)
Display	12.09	2	< .005
Run	10.24	1	< .005
Display x Run	.5	2	N. S.

B. MEAN SCORES

	Visual	Audio	Audio/Visual	Total
Run 1	17.25	18.63	19.63	18.50
Run 2	19.38	19.88	20.00	19.75
Total	18.32	19.26	19.82	19.13

TABLE 2

RESPONSE TIME IN TARGET DETECTION

EXPERIMENT A

A. ANALYSIS OF VARIANCE SUMMARY TABLE

Source of Variation	SS	df	M.S.	F	Level of Significance (p)
Between SS	10,058	23			
Display	5,497	2	2,749	14.4	< .001
Error (SS within groups)	4,021	21	191		
Within SS	4,673	24			
Run	3,037	1	3,037	34	< .001
Display x Run	0	2	--	--	N.S.
Error (Run x SS within groups)	1,876	21	89		

B. MEAN SCORES (SECONDS)

	Visual Display	Acoustic Display	Acoustic/Visual Display	Total
Run 1	76.5	53.9	49.3	59.9
Run 2	57.8	42.0	34.9	44.9
Total	67.1	47.9	42.1	52.4

C. COMPARISON OF DISPLAY MEANS (NEUMAN-KUELS TEST)

Comparison	Level of Significance (p)
Visual versus Acoustic Display	< .01
Visual versus Audio/Visual Display	< .01
Acoustic versus Audio/Visual Display	N. S.

TABLE 3

INTEGRAL OF ABSOLUTE ERROR IN TRACKING TASK

EXPERIMENT A

A. ANALYSIS OF VARIANCE SUMMARY TABLE

Source of Variation	S. S.	df	M. S.	F	p
Between SS	32, 359	23			
Display	1, 202	2	601	. 4	N. S.
Error (SS within groups)	31, 157	21	1, 484		
Within SS	23, 778	72			
Run	5, 303	1	5, 303	14. 6	< . 001
Display X Run	0	2	0		
Error (Run X SS within groups)	7, 644	21	364		
Detection	3, 787	1	3, 787	18. 8	< . 001
Display X Detection	241	2	121	. 6	N. S.
Error (Detection X SS within groups)	4, 224	21	201		
Run X Detection	89	1	89	. 84	N. S.
Display X Run X Detection	284	2	142	1 . 34	N. S.
Error (Run X Detection X SS within groups)	2, 232	21	106		

B. MEAN SCORES

Run	Concurrent Detection Task	Visual Display	Acoustic Display	Acoustic/ Visual Display
1	NO	69.8	59.6	65.9
	YES	85.0	81.9	75.6
2	NO	56.8	54.4	49.8
	YES	70.0	49.8	56.3

Visual	Acoustic	Acoustic/ Visual
70.4	61.4	61.9

Display

NO	YES
59.4	69.8

Concurrent Target Detection

1	2
73.0	56.2

Run

Experiment B

As indicated earlier, Experiment B differed from Experiment A in that fewer subjects were used, an audio/visual display group was not run, and a verbal comprehension task was added. As a consequence of the small sample size, levels of significance up to $p < .25$ are reported.

As in Experiment A, target detection performance was better with the acoustic display than with the visual display. Mean numbers of verbal messages correct (out of 20) are reported in Table 4. As a consequence of the small sample size and highly discrete distribution of scores, statistical analyses were not performed. Accuracy under the acoustical display condition was numerically superior. Response time performance in target detection was also numerically superior under the acoustic display condition (Table 5b). In particular, mean reaction time was nearly 30% lower with the acoustic display than with the visual display. The lack of statistical significance here (Table 5a) is probably a result of large individual differences and a small sample size. It is noteworthy that a significant improvement in performance occurred from Run 1 to Run 2 (Table 5a) and that this improvement, numerically, occurred largely in the acoustic display group (Table 5b).

There were no significant differences in performance on the compensatory visual tracking task associated with the display variable (Table 6a). Numerically superior tracking performance prevailed under the visual display condition. This constitutes the only instance of data, in either Experiment A or Experiment B, suggesting superiority of the visual display. The difference was not statistically significant and the measure was not directly related to target detection performance.

Performance on the verbal comprehension task, included in Experiment B, was numerically better in the acoustic display group than in the visual display group as indicated by accuracy and reaction time scores. The mean accuracy scores comprise Table 7. Due to the small sample sizes and discrete distribution of data, statistical analyses were omitted.

Reaction time measures for the verbal comprehension task (Table 8b) are lower for the acoustic display group than for the visual display group. This difference was not statistically significant (Table 8a).

CONCLUSIONS AND DISCUSSION

The results of initial research, related to the use of acoustic displays in target detection, are in support of additional investigation. With respect to all measures of target detection performance taken, acoustic and audio/visual displays were better than the visual display with no verbal communication task. These differences were all highly statistically significant and held across levels of experience at the task. No differences in concurrent

TABLE 4

TARGET DETECTION ACCURACY

(MEAN NUMBER CORRECT OUT OF 20)

EXPERIMENT B

	Visual Display	Acoustic Display	Total
Run 1	19.0	20.0	19.0
Run 2	18.0	19.0	19.0
Total	18.5	19.5	19.0

TABLE 5

RESPONSE TIME IN TARGET DETECTION

EXPERIMENT B

A. ANALYSIS OF VARIANCE SUMMARY TABLE

Source of Variation	SS	df	M.S	F	(p)
Between SS	2,449	5			
Display	169	1	169	.30	N.S
Error (SS within groups)	2,280	4	570		
Within SS	702	6			
Run	547	1	547	28.8	<.01
Display x Run	80	1	80	4.21	<.25
Error (Run x SS within groups)	75	4	19		

B. MEAN SCORES (SECONDS)

	Visual Display	Acoustic Display	Total
Run 1	63.3	55	59.1
Run 2	61	42.3	51.7
Total	62.1	48.7	55.4

TABLE 6

INTEGRAL OF ABSOLUTE ERROR IN TRACKING TASK

EXPERIMENT B

A. ANALYSIS OF VARIANCE SUMMARY TABLE

Source of Variation	S.S.	df	M.S.	F	(p)
Between SS	4,807	5			
Display	2,054	1	2,054	2.99	<.25
Error (SS within groups)	2,753	4	688		
Within SS	4,317	18			
Detection	4	1	4	.02	N.S.
Display X Detection	433	1	433	1.84	<.25
Error (Detection X SS within groups)	939	4	235		
Run	963	1	963	3.24	<.25
Display X Run	53	1	53	.18	N.S.
Error (Run x SS within groups)	1,187	4	297		
Detection X Run	267	1	267	5.24	<.10
Display X Detection X Run	267	1	267	5.24	<.10
Error (Detection X Run X SS within groups)	204	4	51		

B. MEAN SCORES

Run	Concurrent Detection Task	Visual Display	Acoustic Display
1	NO	60	87
	YES	70	89
2	NO	51	60
	YES	60	60

NO	YES
69	70

Concurrent Target Detection

1	2
76	63

Run

Visual	Acoustic
60	79

Display

TABLE 7

VERBAL COMPREHENSION

(MEAN NUMBER CORRECT OUT OF 20)

EXPERIMENT B

	Visual Display	Acoustic Display	Total
Run 1	13	17	15
Run 2	14	19	17
Total	14	18	16

TABLE 8

REACTION TIME IN VERBAL COMPREHENSION TASK

EXPERIMENT B

A. ANALYSIS OF VARIANCE SUMMARY TABLE

Source of Variation	SS	df	M. S.	F	(p)
Between SS	1,258	5			
Display	21	1	21	.07	N. S
Error (SS within groups)	1,237	4	309		
With SS	1,199	6			
Run	645	1	645	4.67	< .1
Display x Run	9	1	9	.07	N. S.
Error (Run x SS within groups)	545	4	138		

B. MEAN SCORES (SECONDS)

	Visual Display	Acoustic Display	Total
Run 1	57	44	51
Run 2	56	40	48
Total	57	42	50

tracking performance as a result of display type were statistically significant but the acoustic and visual/acoustic displays did result in superior tracking performance across levels of experience. This relationship held for the case in which subjects were simultaneously engaged in target detection and tracking as well as when engaged only in tracking.

With the addition of a verbal communication task, the above results are further supported. No differences attributable to display type were statistically significant but the acoustic displays resulted in better mean performance than the visual display on all measures of target detection performance and of ability to comprehend verbal communication. The visual display did, however, yield superior performance on the concurrent tracking task.

A logical next step would involve extension of this research into displays of two (or more) dimensions of target location. If results of such research were promising, efforts should be directed toward development of "optimum" displays for particular applications. These, in turn, should be evaluated in operational situations.

SELECTION OF ACOUSTIC DISPLAYS OF FLIGHT PARAMETERS

INTRODUCTION

Evaluation of the feasibility of employing acoustic displays of flight parameters in aerospace vehicles is the goal of the remaining experimental work in this program. Research described in this section of the report was addressed to the selection of acoustic displays for later evaluation under simulated flight. "Optimization" of displays was beyond the scope of the effort, but it was necessary to develop displays of sufficient merit to represent the concept of acoustic displays. Such displays were devised on the basis of non-experimental considerations followed by experimental work.

PRE-EXPERIMENTAL CONSIDERATIONS

The flight parameters to be experimentally displayed were chosen on the basis of logical considerations and discussion with X-15 pilots and other relevant personnel. Roll angle (ϕ) was selected in that it requires continual monitoring and thus is a possible factor in visual loading. It is also, in general, of secondary concern to the operator and its control could, perhaps, become more "automatic" under suitable display conditions.

Angle of attack (α) and normal acceleration (g) were the remaining 2 parameters selected for investigation. Angle of attack is of interest in that it requires frequent monitoring and is of critical importance during various maneuvers. There are no flight parameters of interest which are controlled independently from roll angle and angle of attack. Normal acceleration was chosen because it is critical during a restricted portion of profiles representative of the X-15.

During most of a profile, this parameter is not critical and thus it provides an opportunity to examine the feasibility of acoustic displays with respect to presentation of redundant and, possibly, ignorable information.

In general, humans can only make about 7 absolute category judgments among acoustic stimuli differing along a simple dimension (ref. 6). Consequently, acoustic command displays were devised rather than situational displays which would require numerous absolute judgments. The possibility of developing situational acoustic displays is not discounted but such displays would probably require extensive research. A reasonable direction for this effort would involve increasing the number of variable stimulus dimensions in order to increase the operator's channel capacity (ref. 13).

Acoustic displays were based on a carrier frequency of 2000 cps as a result of considerations of discriminability (ref. 9) and minimal masking of verbal communication (ref. 14). The use of a steady 2000 cps tone to indicate "no error" rather than, say, no signal, provides a positive indication of zero error and allows discrimination between this state and a lack of signal due to a display malfunction.

Two of the channels of display were based on frequency modulations as these are readily detectable over large ranges of rates and durations (refs. 9 and 15). A third channel was based upon a binaural amplitude shift and has the following positive attributes:

1. Binaural discriminations are good in noise (ref. 16).
2. The binaural cue is relatively independent from frequency modulations.
3. The binaural cue possesses a "natural compatibility" with left-right commands, such as roll angle.

The binaural cue was based on amplitude differences, which appear to be the major localization cue at about 2000 cps (refs. 10, 17 and 18). Humans can make discriminations within about 5 to 10 degrees in this situation and (ref. 19) through an appropriate relationship between errors and amplitude difference good resolution may be obtained.

The three acoustic channels developed for experimental evaluation are described, in detail, in Appendix B. Briefly, they are:

1. "Wobble:" Sinusoidal modulation of the 2000 cps tone. Modulation occurs at 11 cps for "negative" errors and at 4 cps for "positive" errors. The deviation in frequency is proportional to the magnitude of the error and plus or minus 2000 cps in full scale.
2. "Swoop:" Linear frequency modulation of the 2000 cps tone. Sweep in toward higher frequencies for "negative" errors and toward lower for "positive". Plus or minus 2000 cps is full scale.

3. "Binaural:" Left-right amplitude differences. The amplitude difference is non-linearly related to error magnitude in order to provide greater resolution.

The two frequency modulation displays can be combined by sequential presentation and the binaural display can be superimposed on either or both of these channels. In the research reported here, the binaural display was used to command roll angle as a consequence of the inherent compatability. Wobble and swoop were each used as command displays of angle of attack and of normal acceleration.

METHOD

Apparatus

Experimental evaluation of the displays described above was accomplished through the use of a tracking task. A simulator was constructed which was based on the X-15 dynamics (see Appendix C) with angle of attack, normal acceleration, and roll angle displayed. These parameters could be displayed acoustically and/or visually. The acoustic display possibilities (channel-parameter assignments) were as follows:

1. Roll angle: binaural
2. Angle of attack: wobble or swoop
3. Normal acceleration: wobble or swoop

As noted earlier, all acoustic displays are command displays, whereas the conventional type visual instruments display situational information. Thus, the acoustic displays differ from conventional displays both in sense mode and in type of information displayed. In order to isolate the effects of display mode (acoustic, visual) from effects of type of information displayed (command, sutuational), special visual displays were constructed. These consisted of approximations to the conventional (e. g. X-15) angle of attack indicator, roll angle indicator, and accelerometer. The new instruments had red command needles which were driven, concentrically with the white situation needles, by the same error signals used to drive the acoustic displays. The command needle indicates the correct (commanded) value of the displayed parameter and the white needle displays the actual value.

The command needles, as described above, for the control condition were selected for several reasons:

1. Tracking one pointer with another results in better performance than does keeping a single pointer at a fixed line (ref. 20). Thus, the visual display was partially optimized.

2. The subject's task was to "follow" the commands, as it was with the acoustic displays.

Technically speaking, the above visual display requires pursuit tracking while the acoustic display calls for compensatory tracking (e. g. ref. 21) Consequently, it could be argued that a compensatory visual display would form a more suitable control. It is intuitively doubtful, however, that the visual displays used effectively elicited pursuit tracking, as the situational information provided is of no "value" in performing the required task. The information used by the operator in all cases seems to be as well matched as possible.

The simulator, which is described in detail in Appendix C, consisted of a cockpit with side-stick controller and the three visual instruments described above. Visual instruments could be covered and the 3 parameters could also be displayed acoustically in any of the ways described above. The commanded "flight" profile (tracking task), which is described in detail in Appendix D of this report, was based on an X-15 altitude mission and included drop-off through re-entry phases. Duration of the task was 5 minutes.

Absolute error in roll angle, angle of attack, and normal acceleration were integrated over portions of the flight profile and indicated on a strip chart recorder.

A verbal comprehension task was also provided. A 4-position switch was located at the left of the seat with positions labeled by the integers 1 through 4. Taped messages, verbally commanding switch positions, were presented at unpredictable times and in random order (see Appendix E for details). Qualitative responses (switch position) of the subjects were recorded on the strip chart recorder and total reaction time was recorded on a clock.

The experimenter was provided with a console with provisions for selecting acoustic channel-parameter assignments and parameters to be displayed acoustically. Verbal communication between the experimenter and subject was also provided for.

Procedure and Experimental Designs

Eight NASA personnel with varying degrees of flight and/or X-15 simulator experience served as subjects. The subjects were divided into two groups:

1. Group A - swoop was used to display normal acceleration and wobble was used to display angle of attack under acoustic display conditions.

2. Group B - swoop was used to code angle of attack and wobble was used to code normal acceleration under acoustic display conditions.

For both groups, roll angle was displayed binaurally under acoustic display conditions.

Subjects were run in teams of two with each subject run on alternate trials to reduce fatigue effects. Each team participated in three sessions:

1. First session: all acoustic display conditions involved one acoustically displayed parameter.
2. Second session: all acoustic display conditions involved two acoustically displayed parameters.
3. Third session: all acoustic display conditions involved three acoustically displayed parameters.

The matrices for data analysis, indicating the independent variables for these three sessions are shown in Figures 4, 5 and 6, respectively.

In all cases, a fourth independent variable was trial or experience at the task. The three dimensional matrices, shown in Figures 4, 5 and 6, represent the factorial analysis of variance designs used in data analyses (ref. 11). Display, Flight Phase, and Trial were within subject variables and the order of occurrence of display conditions, within each group of subjects, was counterbalanced for learning effects in a Latin Square arrangement. The Latin Square was balanced for sequence locations (i. e. each display condition occurred equally frequently as a 1st trial, 2nd trial, etc.) and was also balanced for consecutive sequences of two conditions.

During each trial the subject's task was to fly the commanded profile (Appendix D) as accurately as possible and to respond to verbal messages (Appendix E). For each Subject X Display combination, the following training and experimental conditions occurred:

1. 1 minute with visual and acoustic display(s) representing the parameters(s) to be acoustically coded.
2. 1 minute with acoustic display(s) alone.
3. A full trial run which is identical to a data run without verbal messages.
4. Three complete data runs.

Verbal messages consisted of instructions to respond in specific positions on the 4-position switch located at the subject's left console. Sixteen messages occurred during each run and 12 sets of messages were used to avoid learning (and anticipation) of verbal cues.

As indicated above, the 3 data runs under each Subject X Display condition did not occur consecutively but were counterbalanced in a Latin Square

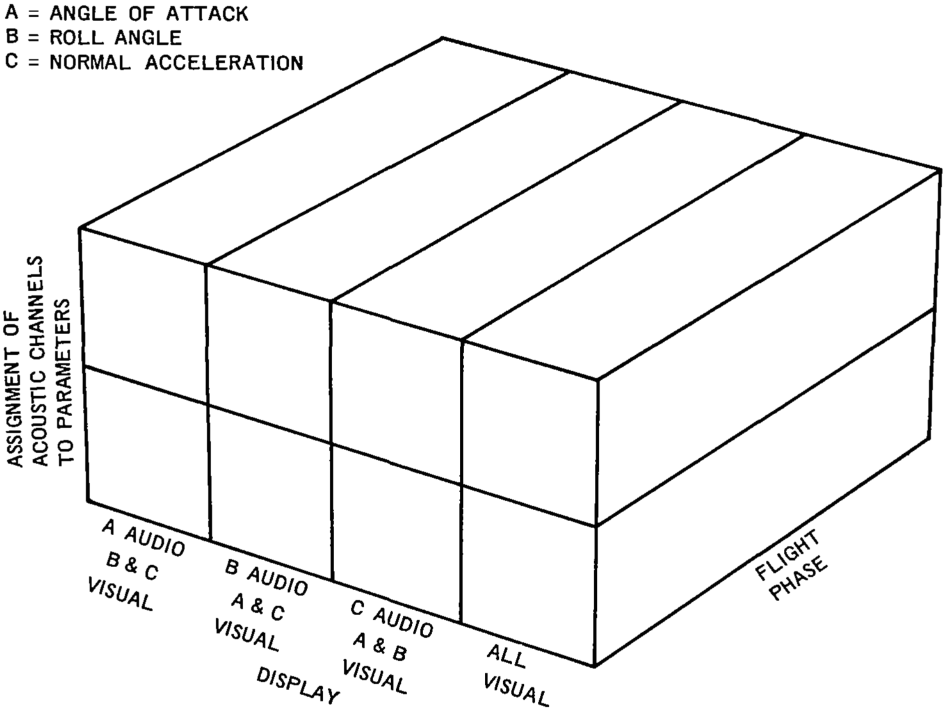

Figure 4: Experimental Design for First Display Selection Session

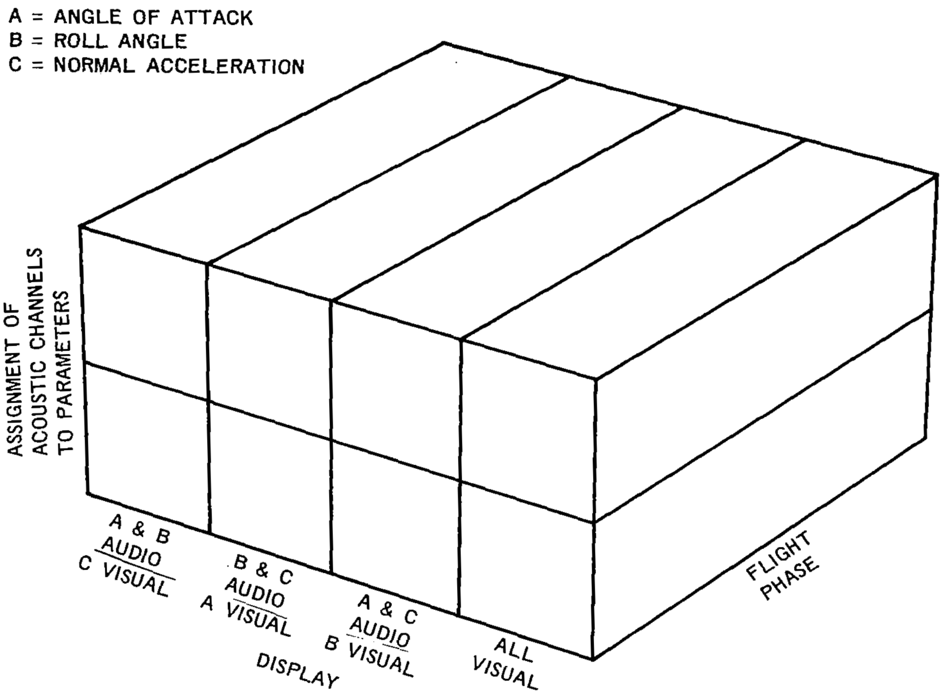

Figure 5: Experimental Design for Second Display Selection Session

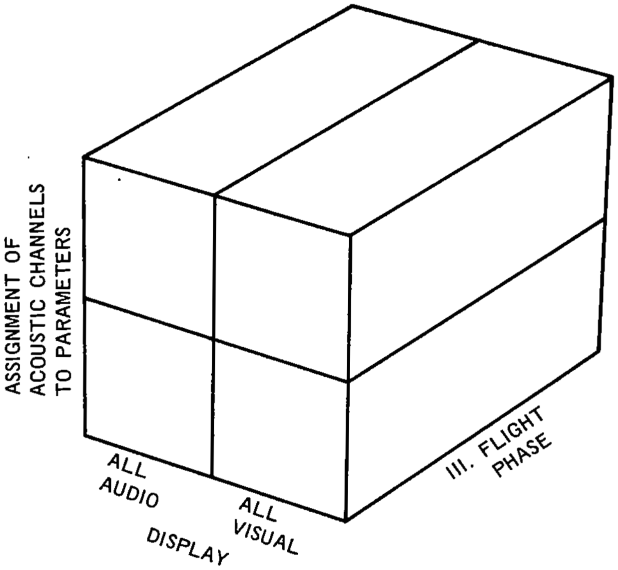

Figure 6: Experimental Design for Third Display Selection Session

arrangement.

The dependent variables recorded during each data run were:

1. The integral of absolute error in angle of attack, roll angle, and normal acceleration.

2. The number of correct responses and total reaction time in responding to verbal messages.

Subjective impressions were also obtained from subjects.

RESULTS

As a consequence of the large amount of data processed in this phase of the program, only the most relevant data summaries and analyses are presented and discussed here. Summaries and analyses of the remaining data comprise Appendix F of this report. They are presented in the same format as is used below. In particular, the only data presented here will be from the final data runs under each conditions. Thus, the following data represent performance following the maximum training which occurred in the study.

The manner in which the flight profile was divided into phases is indicated in Appendix D. Data means presented here are taken over flight phases and are shown as function only of display variables. In all cases data were analyzed following the standard three dimensional factorial analysis of variance design with repeated measures on two factors (e. g. ref. 11, page 319).

Single Acoustic Channel

Data pertinent to single channel acoustic displays are presented in Tables 9 and 10. Of primary interest in Table 9 is that observed performance differences associated with the display variable were statistically significant in angle of attack and roll angle error. It is evident, in Table 10, that inferior performance was measured under some acoustic display conditions than under the all visual display condition. In particular, with the exception of normal acceleration, the acoustic display of a parameter was associated with increased tracking error in that parameter. These findings are not a priori discouraging for several reasons:

1. Subjects were not heavily loaded visually, as they would be in typical applications.

2. In order to provide the necessary flexibility for quickly changing display configuration, there were "dead bands" present (e. g. 1/4 second per second contained no information in the angle of attack wobble display. The remaining 1/4 second was used to insert the

TABLE 9: ANALYSIS OF VARIANCE SUMMARY TABLE FOR FOUR PERFORMANCE MEASURES: ONE ACOUSTIC CHANNEL

Source of Variation	df	Integral of Absolute Error in Angle of Attack		Integral of Absolute Error in Normal Acceleration		Integral of Absolute Error in Roll Angle		Number of Verbal Messages Correct Per Second	
		MS	F	MS	F	MS	F	MS	F
Channel-Parameter Assignment (C-P)	1	.223	1.069	.098	.343	.000	.000	.003	.061
Display (D)	3	1.333	7.527**	.068	.469	.556	9.525***	.054	4.321*
Flight Phase (P)	5	2.292	31.313***	2.403	34.764***	.201	6.557***	The third independent variable, for this performance measure, was trials and not flight phase.	
(C-P) x D	3	.371	2.094	.210	1.440	.063	1.080		
(C-P) x P	5	.256	3.493*	.109	1.574	.026	.851		
D x P	15	.695	9.012***	.090	1.036	.007	.501		
(C-P) x D x P	15	.049	.641	.100	1.150	.009	.636		

* p<.05
** p<.01
*** p<.001

TABLE 10: MEAN PERFORMANCE ON FOUR PERFORMANCE MEASURES, ONE ACOUSTIC CHANNEL

Channel Parameter Assignment Display	α Acoustic	ϕ Acoustic	g Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.616	.344	.517	.412	.472
α - Swoop g - Wobble ϕ - Binaural	.894	.459	.374	.435	.540
Total	.755	.402	.445	.423	.506

A. INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK

Channel Parameter Assignment Display	α Acoustic	ϕ Acoustic	g Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.350	.273	.434	.392	.362
α - Swoop g - Wobble ϕ - Binaural	.430	.326	.245	.267	.317
Total	.390	.299	.339	.330	.340

B. INTEGRAL OF ABSOLUTE ERROR IN NORMAL ACCELERATION

Channel Parameter Assignment Display	α Acoustic	ϕ Acoustic	g Acoustic	All Visual	Total
α -Wobble g -Swoop ϕ -Binaural	.200	.437	.148	.125	.227
α -Swoop g -Wobble ϕ -Binaural	.231	.330	.181	.172	.228
Total	.215	.384	.164	.148	.228

C. INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE

Channel Parameter Assignment Display	α Acoustic	ϕ Acoustic	g Acoustic	All Visual	Total
α -Wobble g -Swoop ϕ -Binaural	.580	.660	.568	.801	.652
α -Swoop g -Wobble ϕ -Binaural	.669	.679	.659	.767	.694
Total	.625	.670	.614	.784	.673

D. NUMBER OF VERBAL MESSAGES CORRECT PER SECOND

swoop display which would not be present in a final display.)

3. Experience with the acoustic displays was significantly less than experience with the visual displays, which were highly similar to current operational displays.

Two observations, based on the data in Table 10, are of particular interest. Although there is no significant effect attributable to channel-parameter assignment (Table 9), the data in Table 10 (Parts A and B) indicate that performance was generally superior with the "wobble" display as compared with the "swoop" display. Thus, angle of attack tracking was superior when α was commanded by the "wobble" display rather than by the "swoop" display and the same relationship prevailed for g-tracking. Also, when "g" was commanded via the "wobble" display, the same order of performance prevailed relative to display of "g" by the "swoop" display.

The second observation of interest, based on the data in Table 10, concerns the "binaural" roll angle display. Although roll-tracking was clearly inferior with the "binaural" display (Table 10C), superior performance occured in angle of attack tracking (Table 10A) and normal acceleration tracking (Table 10B) with the "binaural" display. This suggests that the "binaural" display may have somehow been alleviating operator loading and thus resulting in improved performance on remaining tasks. If, through modifications of the "binaural" display, improved roll-tracking could be obtained without reducing the benefits in tracking of remaining parameters, overall gains would result from such a display.

Two Acoustic Channels

The data collected under two-channel acoustic display conditions were less conclusive than those reported above re one-channel acoustic displays. The analysis of variance summaries reported in Table 11 indicate significant differences in angle of attack and roll angle tracking performance as a function of the display variable but, as is seen in Table 12, these are differences between visual and acoustic displays. For example, in Table 12a it is seen that angle of attack tracking is superior under the two display conditions in which angle of attack was visually displayed. There is no clear indication of superiority of one acoustic display over others.

It should be noted that, relative to all four dependent variables, mean performance was better in the " α wobble" group as compared with the " α-swoop" group. This result is consistent with the results reported in the one-channel acoustic section above.

Three Acoustic Channels

The data reported in Tables 13 and 14 pertain to a direct comparison of the

TABLE 11: ANALYSIS OF VARIANCE SUMMARY TABLE FOR FOUR PERFORMANCE MEASURES: TWO ACOUSTIC CHANNELS

Source of Variation	df	Integral of Absolute Error in Angle of Attack		Integral of Absolute Error in Normal Acceleration		Integral of Absolute Error in Roll Angle		Number of Verbal Messages Correct Per Second	
		MS	F	MS	F	MS	F	MS	F
Channel-Parameter Assignment (C-P)	1	2.727	1.487	.548	1.084	.048	.433	.448	2.670
Display (D)	3	2.000	5.651**	.337	2.867	.788	17.123***	.031	5.869**
Flight Phase (P)	5	2.668	7.490***	1.030	13.807***	.089	2.958*	The third independent variable, for this performance measure, was trials and not flight phase.	
(C-P) x D	3	.809	2.285	.117	.994	.081	1.767		
(C-P) x P	5	.339	.951	.121	1.623	.012	.412		
D x P	15	.405	4.389***	.069	1.741	.020	1.044		
(C-P) x D x P	15	.203	2.201*	.044	1.096	.019	.955		

* p<.05
** p<.01
*** p<.001

TABLE 12: MEAN PERFORMANCE ON FOUR PERFORMANCE MEASURES, TWO ACOUSTIC CHANNELS

Channel Parameter Assignment / Display	$\alpha + \phi$ Acoustic	$\phi + g$ Acoustic	$\alpha + g$ Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.497	.339	.465	.316	.404
α - Swoop g - Wobble ϕ - Binaural	.740	.374	1.068	.388	.643
Total	.618	.357	.766	.352	.524

A. INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK

Channel Parameter Assignment / Display	$\alpha + \phi$ Acoustic	$\phi + g$ Acoustic	$\alpha + g$ Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.270	.214	.282	.211	.245
α - Swoop g - Wobble ϕ - Binaural	.375	.257	.530	.245	.351
Total	.322	.235	.406	.228	.298

B. INTEGRAL OF ABSOLUTE ERROR IN NORMAL ACCELERATION

Channel Parameter Assignment / Display	$\alpha + \phi$ Acoustic	$\phi + g$ Acoustic	$\alpha + g$ Acoustic	All Visual	Total
α -Wobble g -Swoop ϕ -Binaural	.414	.267	.111	.113	.226
α -Swoop g -Wobble ϕ -Binaural	.337	.388	.166	.140	.258
Total	.376	.328	.139	.127	.242

C. INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE

Channel Parameter Assignment / Display	$\alpha + \phi$ Acoustic	$\phi + g$ Acoustic	$\alpha + g$ Acoustic	All Visual	Total
α -Wobble g -Swoop ϕ -Binaural	.644	.805	.773	.844	.767
α -Swoop g -Wobble ϕ -Binaural	.593	.570	.551	.641	.589
Total	.619	.688	.662	.743	.678

D. NUMBER OF VERBAL MESSAGES CORRECT PER SECOND

TABLE 13: ANALYSIS OF VARIANCE SUMMARY TABLE

FOR FOUR PERFORMANCE MEASURES: THREE ACOUSTIC CHANNELS

Source of Variation	df	Integral of Absolute Error in Angle of Attack		Integral of Absolute Error in Normal Acceleration		Integral of Absolute Error in Roll Angle		Number of Verbal Messages Correct Per Second	
		MS	F	MS	F	MS	F	MS	F
Channel-Parameter Assignment (C-P)	1	2.774	6.342*	.983	4.215	.000	.000	.521	3.263
Display (D)	1	3.386	8.306*	1.031	4.663	2.293	38.911***	.046	6.934*
Flight Phase (P)	5	1.355	9.153***	.966	6.412***	.058	3.692**	The third independent variable, for this performance measure, was trials and not flight phase	
(C-P) x D	1	.907	2.225	.316	1.430	.079	1.344		
(C-P) x P	5	.204	1.376	.191	1.265	.009	.593		
D x P	5	.646	3.849**	.208	1.382	.029	1.963		
(C-P) x D x P	5	.101	.600	.074	.490	.018	1.203		

* $p<.05$
** $p<.01$
*** $p<.001$

TABLE 14: MEAN PERFORMANCE ON FOUR PERFORMANCE MEASURES, THREE ACOUSTIC CHANNELS

Channel Parameter Assignment Display	All Acoustic	All Visual	Total
α-Wobble g-Swoop ϕ-Binaural	.423	.242	.333
α-Swoop g-Wobble ϕ-Binaural	.958	.388	.673
Total	.690	.315	.503

A. INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK

Channel Parameter Assignment Display	All Acoustic	All Visual	Total
α-Wobble g-Swoop ϕ-Binaural	.279	.186	.233
α-Swoop g-Wobble ϕ-Binaural	.596	.274	.435
Total	.437	.230	.334

B. INTEGRAL OF ABSOLUTE ERROR IN NORMAL ACCELERATION

Channel Parameter Assignment Display	All Acoustic	All Visual	Total
α-Wobble g-Swoop ϕ-Binaural	.468	.102	.285
α-Swoop g-Wobble ϕ-Binaural	.410	.158	.284
Total	.439	.130	.285

C. INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE

Channel Parameter Assignment Display	All Acoustic	All Visual	Total
α-Wobble g-Swoop ϕ-Binaural	.718	.801	.760
α-Swoop g-Wobble ϕ-Binaural	.623	.638	.631
Total	.671	.720	.695

D. NUMBER OF VERBAL MESSAGES CORRECT PER SECOND

three-channel acoustic display and the three-channel visual display. There are two outstanding conclusions:

1. Performance was significantly better with the all visual display as compared with the all acoustic display.
2. Performance tended to be superior in the "α-wobble" group as compared with the "α-swoop" group.

These results are consistent with those reported above.

Subjective Data

Following each day of data collection subjects were given questionnaires to be completed. (See Appendix G for a sample questionnaire) Subjects were, in essence, asked for general reactions to the experiment, displays, and general concepts being investigated. Responses were highly variable across subjects and hence are not presented here in detail. Salient comments and summaries of some more frequent replies follow:

1. "Wobble" was generally preferred over "swoop."
2. It was frequently stated that large improvements in performance were expected with more practice on the acoustic angle of attack display.
3. The roll display did not provide adequate assurrance of the null (no-error) condition.
4. Normal acceleration was not felt to be a useful parameter to display acoustically.
5. There was some feeling that the "wobble" display was conducive to reversal response errors under small error signals.
6. Reactions to the concepts involved and to the general experimental setting varied from unfavorable to highly positive.

CONCLUSIONS AND DISCUSSION

Data and subjective reactions collected in the "Selection of Acoustic Displays of Flight Parameters" phase were not conclusive. They did, however, provide certain guidelines which were used, together with other considerations, to select acoustic displays for experimental evaluation. General conclusions based upon these data include:

1. The "binaural" roll angle display was a promising one in that there were indications of improved performance on tracking remaining parameters when this display was used. Also, there appeared to be a "natural compatibility" between the acoustic signal and the required response. Subjects' comments concerning the need for increased discriminability near null indicated directions for improving this display.

2. Data indicate superiority of the "wobble" code over the "swoop" code. Increased discriminability of the direction of commands would be desirable for small errors.

3. Angle of attack seemed to be a parameter of substantially greater interest than did normal acceleration.

4. Data suggest that extensive work is needed to render a three-channel acoustic display feasible at the present time and in the present context.

On the basis of these conclusions, two displays were selected for modification in order to improve their suitability. It was hypothesized that the feasibility of such improved displays, when evaluated in the more visually demanding context of a complete simulated profile, would be supported. The two displays selected for modification were the one-channel "binaural" roll angle display and the two-channel "binaural" roll angle plus "wobble" angle of attack display. This particular selection followed directly from the general conclusions listed above. The modifications were derived from considerations of the available literature, applications of logic, and small scale experimentation using local personnel as subjects.

The major steps in the modification procedure are outlined below:

1. The basic carrier frequency was lowered to 500 cps. This allowed the addition of a binaural cue based upon a phase shift, if needed, to increase discriminability, (refs. 10, 17 and 18).

2. The acoustic signal was interupted in order to increase discriminability of the "binaural" cue and to reduce habituation (ref. 10).

3. The function relating the magnitude of the binaural amplitude difference and error magnitude in the "binaural" display was changed. The new function was determined experimentally to achieve discriminability of a .5° change in error magnitude within 1.5° of null and a 1° change within 5° of null. Five degrees of error in roll angle corresponded to full scale.

4. The "wobble" command for angle of attack was modified in that:

a. The "increase angle of attack" command was changed from a fast (11 cps) sinusoidal frequency modulation to a fast (10 cps) square wave frequency modulation with increasing frequency only. Full scale was +500 cps.

b. The "decrease angle of attack" command, still a 4 cps sinusoidal modulation, had a full scale ±250 cps. In both cases, full scale corresponded to a 10° error in angle of attack.

See Appendix H for a detailed description of these modified acoustic displays, including a schematic of the signal generating circuit.

Three local personnel flew the profile used in the major experimental portion of this phase with the modified acoustic displays and the all visual display. Angle of attack error and roll angle error were measured following several practice runs. For all subjects mean performance at angle of attack tracking was at least as good with the acoustic displays as with the all visual display. With respect to roll angle tracking, two of the subjects exhibited slightly poorer mean performance under acoustic display conditions, whereas the third subject's performance was about the same under all display conditions.

As a result of the above considerations, it was concluded that the modified acoustic displays (See Appendix H) were suitable for use in the remaining experimental phase of the program. That is, examination of the modified acoustic displays under simulated flight appeared relevant to the evaluation of the acoustic display concept.

EXPERIMENTAL EVALUATION OF ACOUSTIC DISPLAYS OF FLIGHT PARAMETERS

INTRODUCTION

In the final phase of this program, the two "modified" acoustic displays described above (See Appendix H) were evaluated under simulated flight conditions. These displays consisted of a "binaural" roll angle command plus "wobble" angle of attack command display. These codes were used in "straight" audio command displays and to acoustically display "augmented" commands, that is, commands which were a function of the error and its first two derivations with respect to time, (refs. 2 and 22). Conventional visual and command visual display conditions were also run in order to control for type of information displayed (situational, command) was well as sense mode (visual, acoustic).

METHOD

Apparatus

Display evaluation was accomplished through analysis of performance measures and subjective reactions in the context of simulated X-15 missions. For this purpose a simulated X-15 cockpit was constructed in a capsule with an opaque canopy which served to avoid instrusion by extraneous outside stimuli. The simulator instruments were driven in 6 degrees of freedom through analog equipment, providing for flying of portions of an altitude mission. All of the operational instruments necessary for performance of the primary flight task were simulated in realistic form. Remaining instruments, such as warning lights and engine instruments, were simulated by photographic decals.

A model of the X-15 side-stick controller was constructed and installed. As in the operational controller, the trim knob, through a servo-motor, physically repositioned the side-stick. During ballistic portions of the profile, the side-stick operated as a reaction controller. Rudder pedals and throttle control were operational in the cockpit and a mission elapsed time clock was activated by "on" movements of the throttle control. A 4-position switch was mounted at the left side of the cockpit and was used for responses in a verbal comprehension task which was effected through a prerecorded tape, as in the previous phase of the program.

Provision was made for displaying roll angle or roll angle plus angle of attack by command visual displays, command acoustic displays and augmented command acoustic displays (See Appendix I) in addition to presentation on conventional visual displays. Dampers in the longitudinal mode could be eliminated. Intercoms were installed for communication between the subject and the experimenter. The cockpit and experimenter's console are described in detail in Appendix J and a description of the analog portion of the simulation comprises Appendix K of this report.

All subjects' tasks were based upon the altitude mission described in Figure 7. Provisions were made for collection and recording of the following data (See Appendix K):

1. Integral of absolute error in angle of attack over 120 seconds during climb-out[3].
2. Variance (mean square) of absolute error in angle of attack about its mean value over 120 seconds during climb-out[3].
3. Integral of absolute error in roll angle over 120 seconds during climb-out[3].

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[3] 5 to 125 seconds after drop-off.

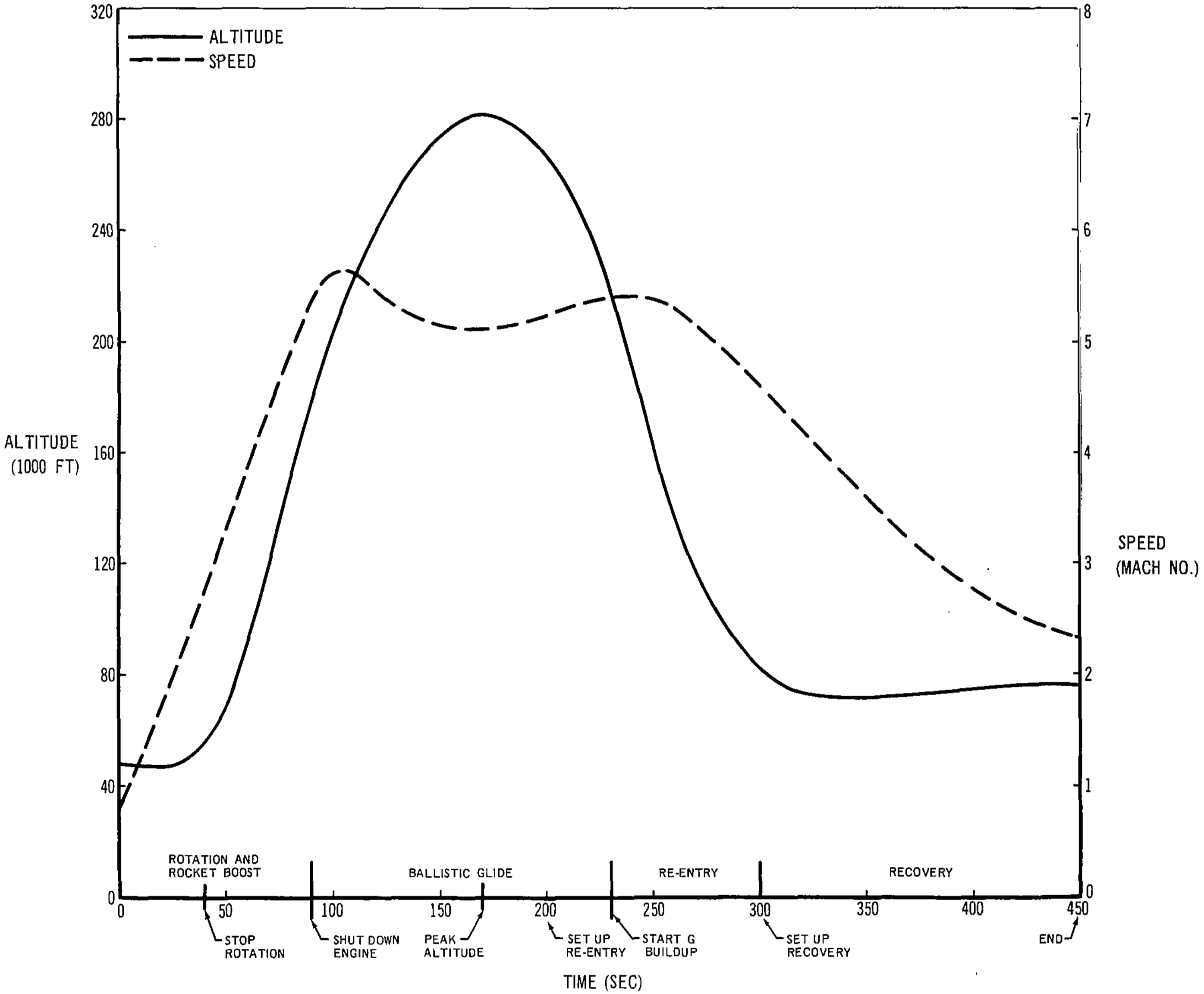

Figure 7: Mission Profile Used in Evaluation Phase

4. Variance of absolute error in roll angle about its mean value over 120 seconds during climb-out[3].

5. Peak altitude.

6. Re-entry angle of attack.

7. Altitude at 310 seconds.

8. Integral of absolute error in angle of attack over 120 seconds during "level" flight[4].

9. Variance of absolute error in angle of attack about its mean value over 120 seconds during "level" flight[4].

10. Integral of absolute error in roll angle over 120 seconds during "level" flight[4].

11. Variance of absolute error in roll angle about its mean value over 120 seconds during "level" flight[4].

12. Responses to verbal messages.

13. Total reaction time elapsed in responding to verbal messages.

The experimenter's console provided for all necessary control, including:

1. Start and reset of the program.
2. Operation of verbal comprehension task.
3. Selection of appropriate displays.
4. Selection of presence or absence of longitudinal dampers.
5. Communication with the subject.
6. Recording of all data.

Procedure and Experimental Design

Eight NASA personnel served as subjects and consisted of an X-15 pilot, two research pilots, four pilots with Navy experience and one private pilot. The

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[3] ibid

[4] 320 to 440 seconds after drop-off.

subjects were divided into two equal sized groups:

1. Group A - Roll angle was the only experimentally displayed flight parameter.

2. Group B - Both roll angle and angle of attack were experimentally displayed flight parameters.

The subjects were run in teams of two with each subject run on alternate trials to reduce fatigue effects, as was done in the previous phase. Each team participated in a training session and a data collection session, which will be described later.

The experimental design (ref. 11, page 319) used in this phase is described in Figure 8. Each group of subjects was run under 4 experimental display conditions:

1. Conventional visual display.

2. Command visual display for experimental parameter(s).

3. Command acoustic display for experimental parameter(s), (See Appendix H).

4. Augmented command acoustic display for experimental parameter(s).

In each run the subject's task was to fly the commanded profile in Figure 7 as accurately as possible and, during data collection runs, to respond to verbal messages (Appendix L) The portion of the profile between 300 and 450 seconds after drop-off is referred to as "level" flight. During this interval, noise ("turbulence") was introducted in the roll axis and, as is seen in the Results section, was associated with increased roll angle error.

During the training session, following general orientation concerning the program, the following events occurred for each subject X display condition (See Appendix M for instructions to subjects under a typical condition and for profile description sheets).

1. Verbal description of display and opportunity for the examination of mission profile.

2. Three 30 second runs for additional familiarization with the display and apparatus.

3. One full run under direct observation of Douglas Aircraft Company personnel familiar with the task. During this run, complete opportunity was afforded for questions concerning all aspects of the task.

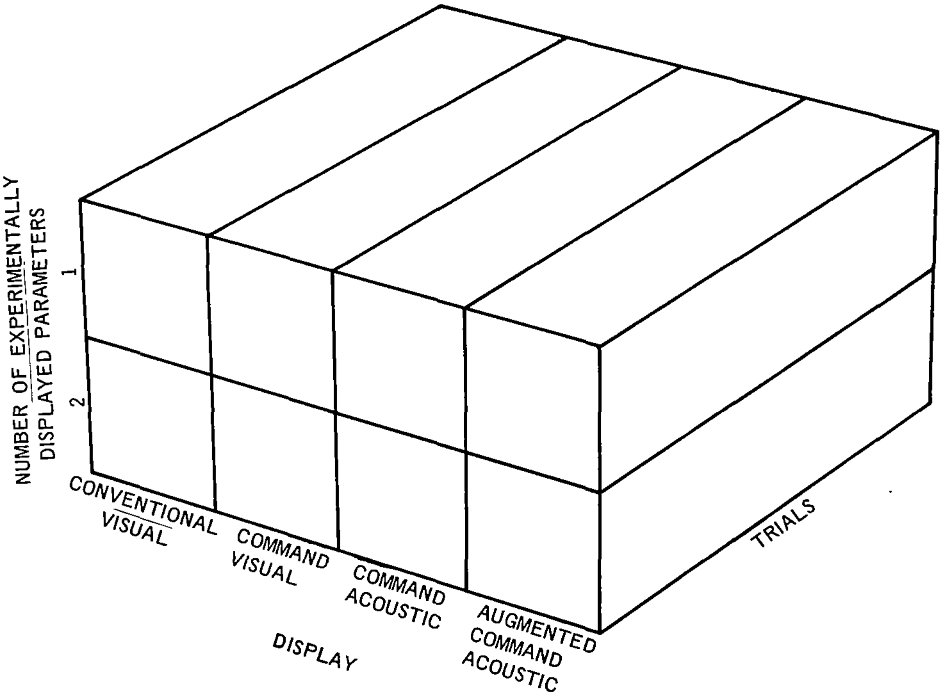

Figure 8: Experimental Design for Acoustic Display Evaluation Phase

4. Two additional full runs.

The order of occurrence of the three full runs per display condition was counterbalanced for sequence effects according to a Latin Square arrangement within each group of subjects.

During the data collection session, the following events occurred for each subject X display condition:

1. Verbal instruction plus a 30 second run to recall the condition to the subject.

2. Three data runs with all dampers in.

3. Two data runs with longitudinal dampers out during climb-out. In particular, longitudinal dampers were out from drop-off until 170 seconds after drop-off.

The order of occurrence of the various display conditions was balanced for sequence effects, (See Appendix N). All runs with all dampers in preceded runs with longitudinal dampers out during climb-out.

During each data run, 20 verbal messages occurred, (See Appendix M). Each message instructed the subject to move the special switch provided at his left into one of 4 positions. Eight sequences were used and order of messages was random within sequences, so that anticipation of the correct response was not possible. Speed and accuracy were emphasized.

In addition to the dependent variables indicated on page 46 and 48 of the Apparatus Section of this discussion, a questionnaire was collected from each subject (See Appendix O). Opinions and comments were requested concerning displays, the simulation, the experimental setting, and general concepts under consideration.

RESULTS

Data analyses and summaries are presented and discussed in this section for the most relevant performance measures, namely:

- Integral of absolute error in roll angle and angle of attack during climb-out and during "level" flight.
- Absolute error in peak altitude.
- Absolute error in re-entry angle of attack.
- Number of verbal messages correct per second in the verbal comprehension task.

Analyses and summaries of data for the remaining dependent variables comprise Appendix P of this report and are presented in the same format as used below. In all cases, data were analyzed following the standard three dimensional factorial analysis of variance design with repeated measures on two factors (e. g. ref. 11). Relative to each dependent variable, the Analysis of Variance Summary table is presented followed by mean performance scores as a function of display variables. That is, mean scores were averaged over trials. In each instance, with the exception of performance on the verbal comprehension task, there was no statistically significant effect attributable to trials. Although it cannot be concluded from this that performance had reached asympote (i. e. there was no effect attributable to trials), there was no evidence to the contrary and it is reasonable to interpret the performance means over trials as representative of levels of performance

Results are discussed first for "flights" in which all dampers were in. Following this, results are presented for "flights" in which longitudinal dampers were out for the first 170 seconds. In all cases, noise was introduced into the roll channel during the "level" flight portion of the mission. (See Figure 7 for a description of the profile).

All Dampers In

Parameter Tracking

During the climb-out portion of the profile, the least average absolute error in angle of attack occurred under the command visual display conditions, (Table 15). Performance relative to this measure recorded under the acoustic display conditions was superior to performance under the conventional visual display condition. During the "level" flight portion of the profile angle of attack tracking was also numerically best under command visual display conditions (Table 16).

In both climb-out and "level" flight phases, superior roll angle tracking was associated with command acoustic display conditions (Tables 17 and 18). There were no indications, in these data, of advantages attributable to the augmented acoustic displays.

Attainment of Critical Parameter Values

Absolute error in peak altitude, on the average, was best under acoustic display conditions (Table 19). The command visual display was associated with the least average absolute error in re-entry angle of attack (Table 20). These differences were not statistically significant and hence should be interpreted only as indications of possible trends.

TABLE 15: INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK DURING CLIMB-OUT (All Dampers In)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	.115	.041	--
Display	(D)	3	1.992	5.014	≈ .01
Trials	(T)	2	.553	.937	--
N x D		3	1.122	2.824	--
D x T		6	.224	1.200	--
N x T		2	.469	.796	--
N x D x T		6	.160	.860	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	1.546	1.362	1.642	1.451	1.501
2	2.045	0.884	1.585	1.765	1.570
Total	1.796	1.123	1.614	1.608	1.536

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Degrees)

TABLE 16: INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK DURING "LEVEL" FLIGHT (All Dampers In)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	1.571	.548	--
Display	(D)	3	.206	.586	--
Trials	(T)	2	.079	.127	--
N x D		3	.135	.384	--
D x T		6	.467	1.742	--
N x T		2	.420	.670	--
N x D x T		6	.136	.509	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	1.265	.923	1.254	1.187	1.157
2	.894	.884	.975	.851	.901
Total	1.080	.904	1.115	1.019	1.029

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Degrees)

TABLE 17: INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE DURING CLIMB-OUT (All Dampers In)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	.034	2.451	--
Display	(D)	3	.004	2.130	--
Trials	(T)	2	.008	2.178	--
N x D		3	.000	0.169	--
D x T		6	.003	.726	--
N x T		2	.000	.161	--
N x D x T		6	.003	1.012	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	1.65	1.66	1.32	1.48	1.53
2	2.00	2.01	1.81	1.80	1.90
Total	1.83	1.84	1.57	1.64	1.72

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Degrees)

TABLE 18: INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE DURING "LEVEL" FLIGHT (All Dampers In)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	.263	.422	--
Display	(D)	3	.026	1.942	--
Trials	(T)	2	.044	1.371	--
N x D		3	.007	.483	--
D x T		6	.022	.822	--
N x T		2	.029	.902	--
N x D x T		6	.035	1.287	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

Number of Experimentally Displayed Parameters	Display Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	4.10	3.53	3.51	4.08	3.80
2	4.71	4.79	4.47	5.43	4.85
Total	4.40	4.16	3.99	4.75	4.33

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Degrees)

TABLE 19: ABSOLUTE ERROR IN PEAK ALTITUDE

(All Dampers In)

Source of Variation	df	MS	F	p
Number of Exp. Parameters	1	799, 837, 500	1.056	--
Display	3	5, 722, 867	.078	--
Trials	2	61, 583, 450	.341	--
N x D	3	92, 418, 767	1.257	--
D x T	6	128, 765, 366	1.709	--
N x T	2	27, 225, 150	.151	--
N x D x T	6	88, 541, 616	1.175	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	9, 300	8, 800	8, 800	9, 700	9, 150
2	15, 000	15, 000	13, 700	13, 100	14, 200
Total	12, 150	11, 900	11, 250	11, 400	11, 675

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Feet)

TABLE 20: ABSOLUTE ERROR IN RE-ENTRY ANGLE OF ATTACK (All Dampers In)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	.017	.000	--
Display	(D)	3	52.165	1.464	--
Trials	(T)	2	4.350	.124	--
N x D		3	32.964	.925	--
D x T		6	22.310	.858	--
N x T		2	14.744	.419	--
N x D x T		6	32.248	1.241	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	.90	.79	.97	.91	.89
2	.70	.22	.60	.56	.52
Total	.80	.51	.79	.74	.71

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Degrees)

Verbal Comprehension

Performance on the verbal comprehension task did not differ significantly as a function of display conditions (Table 21). There was a statistically significant trial effect, namely performance on the 2nd and 3rd trials was superior to performance on the 1st trial.

Longitudinal Dampers Outs During Climb-Out

Parameter Tracking

Tracking of angle of attack during climb-out did not differ significantly as a function of display (Table 22). It is interesting, however, to note, in Table 22, the extremely low average absolute error in angle of attack under the augmented two-channel acoustic command display condition. In spite of this low error score, angle of attack tracking was significantly better in the one-experimental parameter group.

During the "level" flight phase the only significant effect on angle of attack tracking scores was an interaction effect of display X number of experimental parameters (Table 23). This seems to be a result of the superior performance under acoustic display conditions in the "2-parameter" group as opposed to the indicated superiority of the command visual condition in the "1-parameter" group. Over-all, as a function of displays, the numerically lowest error scores on angle of attack tracking were observed under command visual and command acoustic conditions.

There were not significant performance differences with respect to absolute error in roll angle tracking attributable to any of the variables (Tables 22 and 25). Although differences in magnitude of mean scores were small the lowest error scores were obtained under acoustic display conditions during the climb-out phase. In the "level" flight phase, best roll angle tracking prevailed under command visual and augmented acoustic command conditions.

Attainment of Critical Parameter Values

Across display conditions, the "one-experimental parameter" group produced significantly smaller absolute errors in peak altitude, on the average, than did the "two-experimental parameter" group (Table 26). The opposite relationship existed and was significant with respect to absolute error in re-entry angle of attack (Table 27).

TABLE 21: NUMBER OF VERBAL MESSAGES CORRECT/SECOND
(All Dampers In)

Source of Variation	df	MS	F	p
Number of Exp. Parameters	1	.025	.022	--
Display	3	.250	1.829	--
Trials	2	.701	4.405	< .05
N x D	3	.108	.793	--
D x T	6	.045	.777	--
N x T	2	.027	.170	--
N x D x T	6	.070	1.197	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	1.231	1.257	1.163	1.344	1.249
2	1.301	1.462	1.083	1.277	1.281
Total	1.266	1.360	1.123	1.310	1.265

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

TABLE 22: INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK DURING CLIMB-OUT (Longitudinal Dampers Out During Climb-Out)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	238.031	11.061	< .05
Display	(D)	3	27.416	.545	--
Trials	(T)	1	51.707	1.544	--
N x D		3	28.582	.568	--
D x T		3	9.463	.125	--
N x T		1	39.378	1.176	--
N x D x T		3	10.924	.144	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	2.638	2.652	2.542	2.625	2.614
2	6.137	7.373	9.343	3.033	6.471
Total	4.388	5.012	5.942	2.829	4.473

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES (In Degrees)

TABLE 23: INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK DURING "LEVEL" FLIGHT. (Longitudinal Dampers Out During Climb-Out)

Source of Variation	df	MS	F	p
Number of Exp. Parameters	1	30.815	3.806	--
Display	3	.311	.643	--
Trials	1	.526	.429	--
N x D	3	1.720	3.550	<.05
D x T	3	.447	.544	--
N x T	1	.465	.379	--
N x D x T	3	.214	.260	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	2.646	1.791	2.305	2.699	2.360
2	1.046	1.336	0.793	0.714	.972
Total	1.846	1.564	1.549	1.706	1.666

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES.

(In Degrees)

TABLE 24: INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE DURING CLIMB-OUT (Longitudinal Dampers Out During Climb-Out)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	.007	.043	--
Display	(D)	3	.005	2.283	--
Trials	(T)	1	.001	.182	--
N x D		3	.004	1.984	--
D x T		3	.013	2.835	--
N x T		1	.008	1.074	--
N x D x T		3	.009	1.991	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	3.03	2.57	2.38	2.28	2.57
2	2.37	2.40	2.22	2.43	2.36
Total	2.70	2.49	2.30	2.36	2.47

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES
(In Degrees)

TABLE 25: INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE DURING "LEVEL" FLIGHT. (Longitudinal Dampers Out During Climb-Out"

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	.029	.095	--
Display	(D)	3	.012	.640	--
Trials	(T)	1	.011	1.241	--
N x D		3	.045	2.346	--
D x T		3	.041	1.903	--
N x T		1	.001	.078	--
N x D x T		3	.002	.090	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	6.23	4.76	5.54	4.45	5.25
2	4.51	4.81	4.76	5.20	4.82
Total	5.37	4.78	5.15	4.82	5.04

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Degrees)

TABLE 26: ABSOLUTE ERROR IN PEAK ALTITUDE

(Longitudinal Dampers Out During Climb Out)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	5,314,410,000	8.570	< .05
Display	(D)	3	106,564,233	.806	--
Trials	(T)	1	82,355,700	.296	--
N x D		3	213,761,433	1.616	--
D x T		3	882,877,166	2.355	--
N x T		1	423,330,300	1.524	--
N x D x T		3	453,322,500	1.209	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	21,900	7,900	15,600	14,900	15,075
2	22,200	20,600	18,700	21,000	17,850
Total	22,050	14,250	17,150	17,950	16,463

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Feet)

TABLE 27: ABSOLUTE ERROR IN RE-ENTRY ANGLE OF ATTACK
(Longitudinal Dampers Out During Climb-Out)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	828.144	9.022	< .05
Display	(D)	3	278.133	2.873	--
Trials	(T)	1	26.484	.418	--
N x D		3	47.752	.493	--
D x T		3	392.002	3.158	≈ .05
N x T		1	64.040	1.012	--
N x D x T		3	82.300	.663	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	1.80	1.82	1.29	2.50	1.85
2	1.28	1.21	1.37	1.88	1.44
Total	1.54	1.57	1.33	2.19	1.64

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES
(In Degrees)

With regard to display mode, the visual command display was associated with best peak altitude performance and performance under both acoustic display conditions was better than under the conventional visual display condition. The least absolute re-entry angle of attack error was achieved under the command acoustic display condition and this seems attributable, at least in part, to the extremely low error achieved by the "one-experimental parameter" group under this condition.

Verbal Comprehension

As under the "all dampers in" condition, performance on the verbal comprehension task did not differ significantly as a function of display variables (Table 28). Performance was significantly better on the second trial than on the first, which is also consistent with the results from the "all dampers in" condition. (See Appendix P for additional data.)

Subjective Data

Each subject, following the data collection session, was given a questionnaire (See Appendix O for a blank form) to complete. Opinions were requested concerning the simulation, displays, and general concepts under examination. General opinions and summaries of some more frequent replies follows:

1. In general subjects felt that simulation results were at least "moderately" applicable to the operational situation.
2. Most subjects felt that acoustic displays have potentional application in aerospace vehicles. Two subjects were highly positive in this opinion and one was negative.
3. Only one subject felt that the auditory codes used were not appropriate.
4. The choice of experimentally displayed parameters was generally felt to be appropriate for evaluation of the concepts under investigation by subjects in the group which had angle of attack and roll angle acoustically displayed. In the "roll angle only" group, half did not.
5. All but one subject found the acoustic displays less annoying than "slightly." None reported interference between verbal messages and acoustic display signals.
6. Reactions to the program and the concept of acoustic displays varied from unfavorable to highly positive.

TABLE 28: NUMBER OF VERBAL MESSAGES CORRECT/SECOND (Longitudinal Dampers out During Climb-Out)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	.478	.542	--
Display	(D)	3	.094	.898	--
Trials	(T)	1	.331	6.022	< .05
N x D		3	.102	.981	--
D x T		3	.051	.895	--
N x T		1	.036	.654	--
N x D x T		3	.087	1.526	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	1.081	1.073	1.078	1.082	1.079
2	1.247	1.473	1.165	1.122	1.251
Total	1.164	1.273	1.121	1.102	1.165

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

CONCLUSIONS AND DISCUSSION

In general, relative to the dependent variables discussed above, performance under acoustic display conditions was as good as or better than performance under the conventional visual display condition. In some cases, there were indications of superiority of performance with the command visual displays. These results, overall, are highly suggestive of potential advantages of acoustic displays in that prior experience to subjects probably favored performance on the conventional displays. Extensive training with acoustic displays might result in clear performance increments with such displays and empirical evaluation of these conjectures is clearly appropriate.

There were, by and large, no advantages of display augmentation indicated in the data. The concepts of "augmentation" and, more specifically, "quickening", should not be excluded on this basis, however, in that the literature contains various indications of merit in application of these concepts, (see, e.g., refs. 2 and 22). Limitations in sample size as well as methodological difficulties inherent in drawing conclusions of "no-difference" (e.g. ref. 11) should be considered when evaluating the data presented here in the context of other results which favor display augmentation.

Increased opportunity to systematically develop acoustic displays would have been highly desirable. It is reasonable to hypothesize that additional "optimization" research, including parametric studies concerning the relevant acoustic variables, would yield acoustic displays of greater merit. Such displays might, in turn, result in increases in operator performance.

The results also indicated superiority of the command visual displays relative to some of the performance measures. The above remarks concerning lack of experience and of display "optimization" apply to the command visual displays and, as in the case of the acoustic displays, potential applicability is supported.

AREAS FOR FURTHER STUDY

Various experimental and a priori considerations, discussed in the Introduction of this report, suggested advantages to be gained through the use of acoustic displays. These considerations, together with results and experience acquired during conduct of the research program reported herein, lead to the following recommendations:

1. Small scale flight testing of an acoustic display in a suitable vehicle and with appropriate safety precautions would be valuable at this time. It would contribute to evaluation of the validity of related simulation research, such as that reported here, and would provide more realistic assessment of pilot reaction. The binaural roll angle display is very suitable for such an application in that it is relevant

to performance and yet not essential and thus allows for initial evaluation with minimum risk.

2. Specification of additional potential applications of acoustic displays is needed. The location of appropriate contexts for evaluation of concepts such as acoustic displays comprises a critical phase in overall evaluation and must not be neglected.

3. "Optimization" of new displays, as well as of those reported here, is essential and should include:

   a. Development of display concepts compatible with the intended application.

   b. Specifications of appropriate values of display parameters, such as frequencies and intensities, for the display concept.

   c. Examination of additional refinements, such as inclusion of the ability to "tailor" displays to requirements of individual operators. It might be the case, for example, that the intensity of a given acoustic display could be adjusted, within limits, by the operator with no unacceptable performance decrement. In this manner, possible undesireable effects such as "annoyance" can be reduced. The possibility of adopting displays to compensate for deficiencies in operators' sensory abilities, such as frequency discrimination, should also be considered.

4. Evaluation of experimental displays is needed. Emphasis should be on adequate training, controlled empirical research, and the inclusion and measurement of opinions of pilots and other relevant personnel. Flight tests are obviously desireable and should be incorporated wherever feasible.

5. Applicability of the above remarks is not limited to acoustic displays. Similar research programs are appropriate for command visual displays, for example.

In general, the importance of display research is increasing with the growing complexity of man-machine systems. Display improvement should comprise a major approach to the solution of these system problems, in addition to approachs which emphasize modifications to control systems. The capacities of the human operator can be adequately utilized only when he is presented with a suitable task. The appropriate displaying of required information is a substantial component of a "suitable task" and requires consideration which is consistent with its importance.

January, 1966
Douglas Aircraft Company, Incorporated
Long Beach, California

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APPENDIX A

EXPERIMENTAL APPARATUS AND PROCEDURE FOR TARGET DETECTION PHASE

Five separate subsystems comprised the experimental apparatus for this phase of the investigation. Timing and switching of targets and display signals was done by the tape and relay system shown in Figure A1. An explanation of typical sequencing follows in a later paragraph. Targets and auditory cues were generated by photographic slide projectors and audio oscillators, respectively, and were presented to the subject at appropriately timed intervals. During the last portion of this phase, an auditory communication task was added. A set of eight nonsense syllables was recorded in a random pattern and played back to the subject during an experimental run. Response by the subject to targets was through a 4-position switch within reach of the subject's left hand. A similar switch was provided for auditory communication responses. During the entire duration of an experimental run, the subject was asked to perform a secondary compensatory tracking task, presented as a moving ring-like target on an oscilloscope screen.

A detailed explanation of each subsystem is presented in the following paragraphs.

TIMING AND SWITCHING

Prior to the beginning of the experiment, a program describing the time and position of presentation of each target and display signal (target location cue) was written. Intervals between target presentations varied from 30 to 90 seconds; these intervals being programmed as pulses on magnetic tape. Since the display (target location cue) signal could indicate any one of 5 lateral positions corresponding to target position, these positions were programmed on five decks of a 25 position stepping switch. Photographic slides were then made and arranged in sequence corresponding to the stepping switch program. A typical sequence of events then proceeded as follows:

Before start, the PACE computer was held in the RESET mode by built-in relays and by the START switch on the operator's console. As the START switch was put into the starting position, the Ampex 601 tape recorder began the tape transport and the PACE computer went into HOLD. Pulse number O (start pulse) then began a sequence of events; relay K_6 pulled in momentarily, latching K_7 which armed the stepping switch and

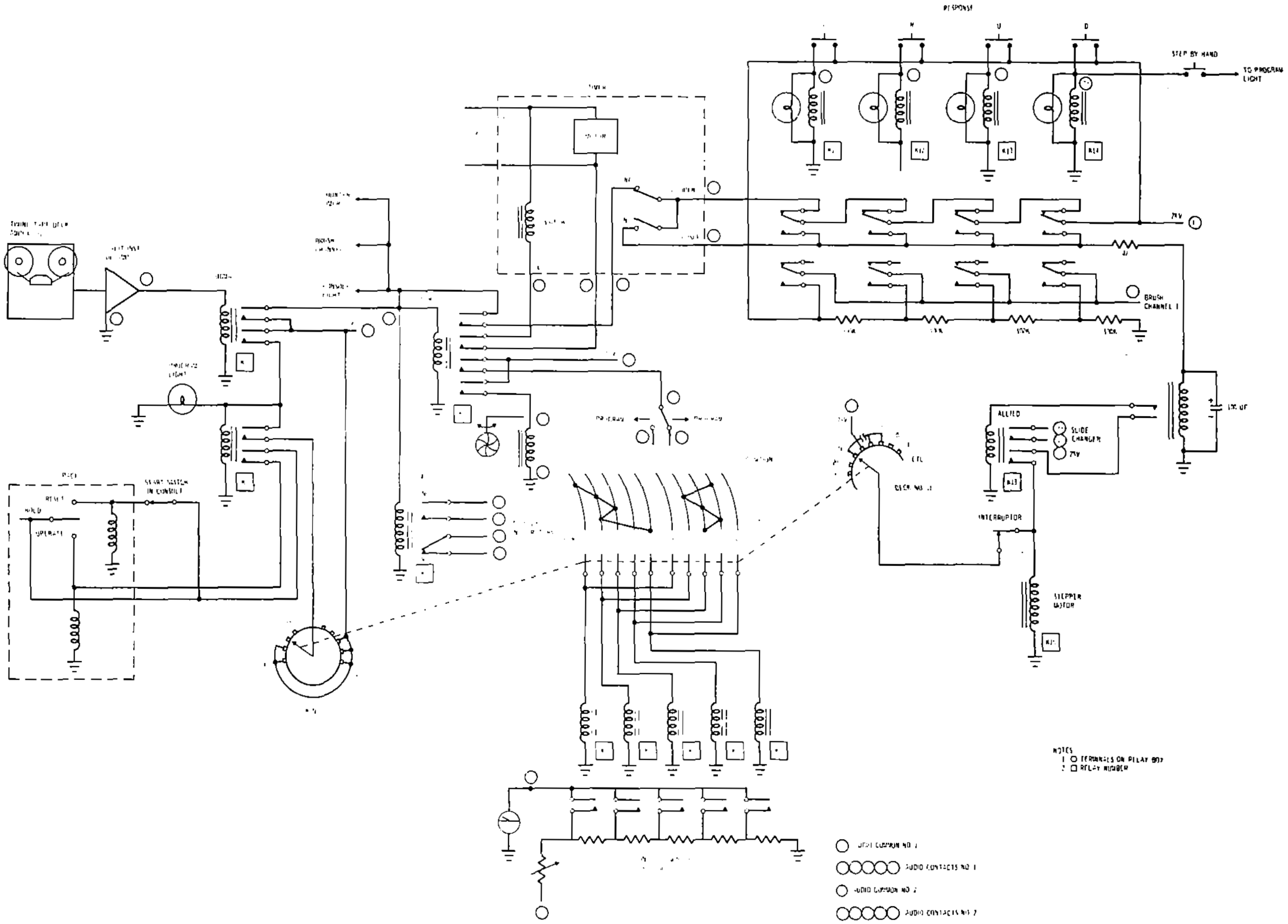


Figure A1: Tape and Relay System Used in Target Detection Phase lit the program light. A second set of contacts on K_7 immediately put the PACE computer into OPERATE, starting tracking error integration. Contacts on K_6 also latched K_9 and K_8. K_8 connected the appropriate PACE integrator to accumulate tracking error during tracking while engaged in target detection. Contacts on K_9 connected power to the stepping relay decks energizing the corresponding relay from K_1 - K_5, opening the slide projector shutter and energizing the timer clutch to start recording reaction time. Since pulse O was used only to start the computer, no target or cue was presented to the subject. At the end of a predetermined interval, the timer momentarily closed a set of contacts applying a pulse to relay K_{10} which advanced the stepping switch to position 1 and the slide projector to slide 2 (target 1). When pulse No. 1 arrived, the same sequence of events occured and slide No. 1 was presented. The corresponding relay from K_1 - K_5 was closed applying an appropriate voltage to the cue meter or the auditory cue generator. One of two things could now happen. The subject could respond by closing a response switch thus closing one relay from K_{11} - K_{14}. One contact on this relay supplied a response signal to a Brush chart recorder, the other contact closed relay K_{10}. Contacts on K_{10} in turn changed the slide and advanced the stepper switch to the next position. When a subject response was made relay K_9 lost its holding power and droped out letting the shutter close and switching the PACE integrators to accumulate error during tracking while not engaged in target detection, If, on the other hand, the subject did not respond to the target cue within a specified time (10 seconds) the timer momentarily closed contacts parallel to the subject response switches. The reset part of the cycle was thus automatically accomplished. Relay K_{16} was incorporated to prevent a double response by the subject by providing a slight time delay before K_{10} could be activated.

AUDIO AND VISUAL DISPLAY SIGNAL GENERATION AND PRESENTATION

Auditory or visual display signals were presented to the subject to aid in the location of a target. Visual information was in the form of a meter deflection corresponding to target position. Thus, the target could be straight ahead (meter reading straight up) or displaced laterally to the right or left by 20 or 40 degrees (meter reading 20 or 40 degrees right or left). Above the target screen were located 5 loudspeakers at the corresponding lateral positions. Concurrently a gapped circle target appeared in the appropriate area among the background circles on the target screen.

Audio and visual display signals could be applied individually or together since completely separate circuits were provided for their presentation. As any relay from K_1 - K_5 was energized two contacts on the particular relay closed. One contact applied a voltage from the divider shown in Figure A1 to the subject's control panel. A second contact applied a

500 cps interrupted tone to the appropriate loudspeaker behind the subject's screen.

SUBJECT RESPONSE AND RECORDING

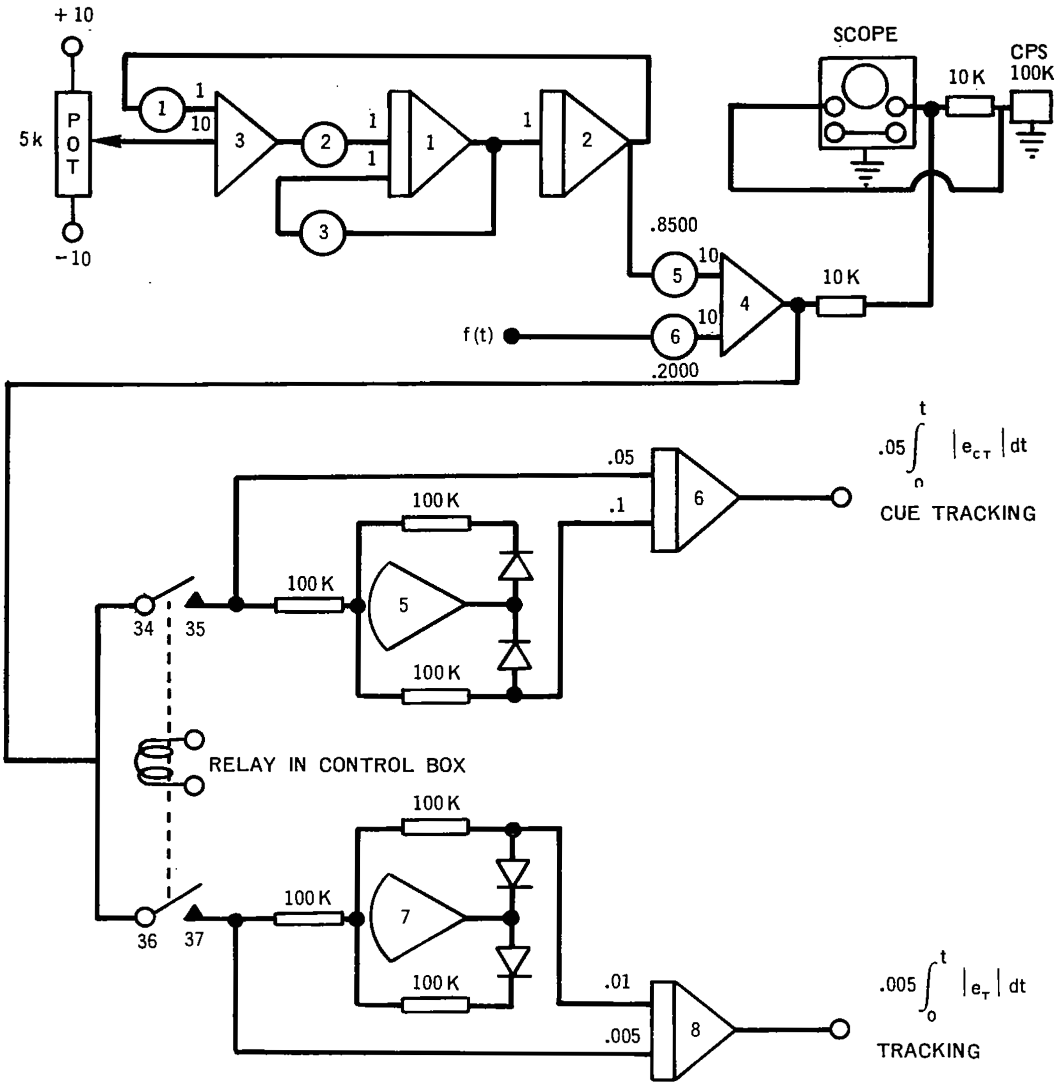
Upon presentation of a target and visual and/or auditory display signals, the subject's response was to move a 4-position switch in the direction of the gap of the target ring (Figure A2). The response was indicated on a Brush chart recorder, response time was accumulated on an electric timer, the slide and stepper switch advanced to the next position and the slide projector shutter closed. The apparatus was now armed for the occurrence of the next timing pulse.

AUDITORY COMMUNICATION

Several experimental runs were made using an additional verbal communications task. Eight 30% association value nonsense syllables were selected and recorded at random at time intervals varying from 20 to 40 seconds between syllables. Four of these syllables were called significant and required a response by the subject. A 4-position switch similar to the target response switch was provided, each position corresponding to a significant syllable. The subject's response, as well as the occurrence of a significant syllable, was recorded on a strip chart recorder.

TRACKING

The subject's secondary tracking task was displayed on an oscilloscope screen on the simulated instrument panel (Figure A2). Figure A2 shows the instrumentation used to generate and score the compensatory task. A filtered gaussian noise function f (t) was recorded on tape and summed with the subject's response. The subject reacted to the resultant error signal. At the same time the absolute error signal was integrated and displayed for two modes of tracking: tracking while concurrently engaged in target detection from amplifier 8, and tracking while not engaged in target detection from amplifier 6. Due to the large differences in times between the two modes, the gain of amplifier 6 was made 10 times the gain of amplifier 8. Corresponding corrections were therefore made during data reduction.



f(t) RANDOM NOISE
TAPE INPUT
ACTUAL NOISE USED
IS INDEXED TO ZERO
100 FT FROM END
SO 16310001

Figure A2: Instrumentation for Generation and Scoring of Compensatory Tracking Task

APPENDIX B

ACOUSTIC DISPLAYS USED IN THE ACOUSTIC DISPLAY SELECTION PHASE

The acoustic displays employed in this program were of the command-display type. In general, corrections of longitudinal errors were commanded by frequency modulations and corrections of lateral errors were commanded by an intensity (loudness) difference between ears.

The signal, in all cases, was a harmonic free vibration produced binaurally in a pair of earphones. The electrical signal which drove the earphones was produced by an oscillator. The frequency of this oscillator could be controlled over a predetermined range by means of a direct current voltage level. This type of device is known as a "voltage controlled oscillator" and will henceforth be referred to as the V. C. O. The output equation for the V. C. O. is:

$$\text{frequency (in c.p.s.)} = 500\text{x (D.C. voltage level)}$$

The binaural effect was produced by forming a volume differential between the ears. This effect was produced by passing the output of the V. C. O. into one of the inputs of each of two multipliers. The other input to these multiplied by summing the error signal with a constant. This was done for each multiplier with the exception that the signs of the constant were different. The outputs of the multipliers were connected one to each earphone. (See Figures B1 and B2).

We have:

$$\{.5\text{ (error signal)} + .5R\}\ \{\text{V.C O signal}\} = V_1$$

$$\{.5\text{ (error signal)} - .5R\}\ \{\text{V.C O. signal}\} = V_2$$

where R was a reference level and V_1 and V_2 were used to drive the two earphones.

When the error was zero, one-half of the reference level was used to drive each earphone. If the error was some "positive" value, the level in one ear would be increased while that of the outer ear would be decreased. The error signal was scaled so that it never exceeded R). The opposite took place for a "negative" error.

During the investigation three parameters were displayed. These were: error in angle of attack, error in load factor, and error in roll angle. The error signals were generated as follows:

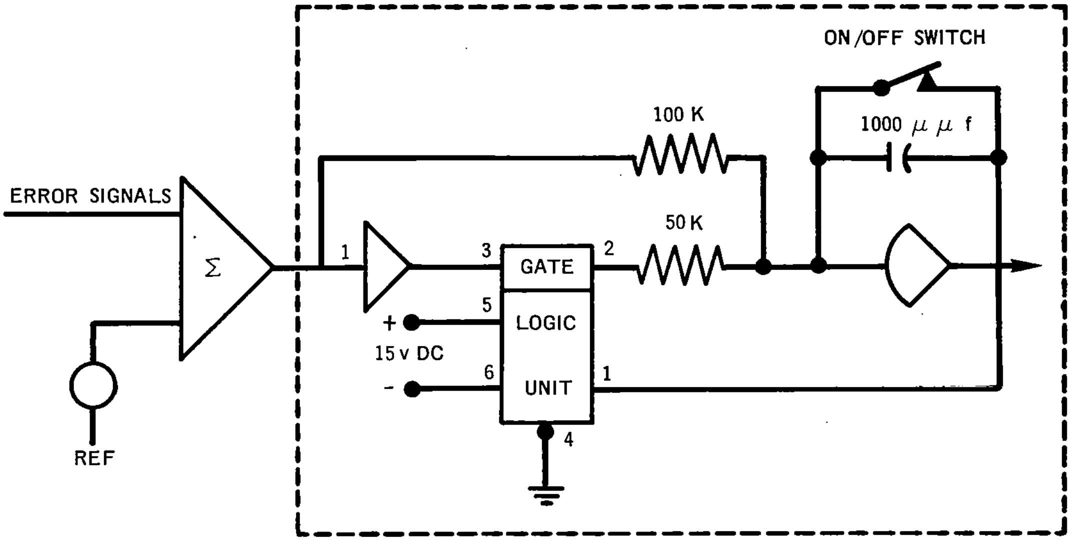


Figure B1: Voltage Controlled Oscillator

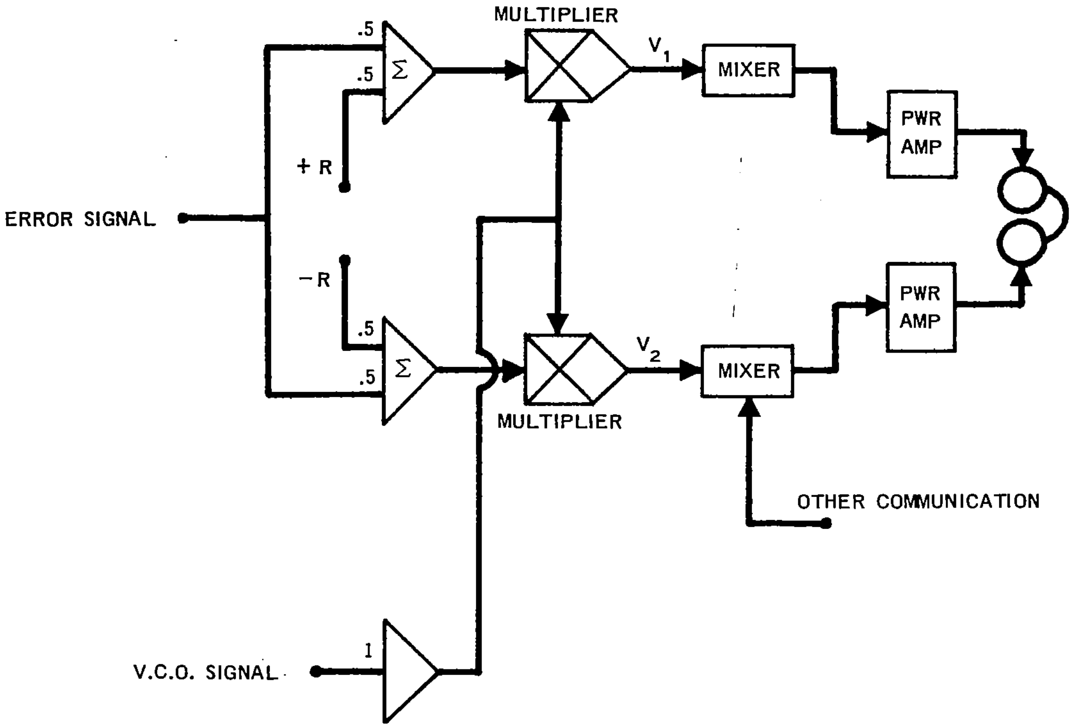


Figure B2: Binaural Cross Over

1. For each of the three dynamic variables a command variable was formed which was a function of time. (i. e., this command indicated the "correct" value of the dynamic variable at any given time).

2. The command variable was compared with the dynamic variable, and the difference was used as the error signal.

3. This error signal was in the form of a direct current voltage level which was used to drive the auditory display.

Two acoustic channels were used to command longitudinal parameters. Each channel was used to display both angle of attack and load factor under different experimental conditions. With one acoustic channel, the displayed parameter was commanded by oscillatory change in frequency. As can be seen in Figure B3, a "positive" error produced a 4 c. p. s. sinusoidal modulation of the frequency of the signal, which was interpreted as a command to decrease, say, angle of attack. An error in the "negative" direction caused an 11 c. p. s. sinusoidal modulation of the frequency which constituted a command to increase say angle of attack. Finally, as can be seen in the last part of the sample error (Figure B3), the magnitude of the frequency change became smaller as error was reduced and larger as error was increased.

The modulation frequencies of 4. c. p. s. and 11 c. p. s. were chosen in that they were low enough to be discriminable, yet high enough to be out of range of error frequency. The difference between the two modulation frequencies was great enough so that there was no difficulty in distinguishing between them.

With the second acoustic channel used to command longitudinal paramers, the displayed parameter was commanded by means of a frequency change which was the integral of the error computed over a . 25 sec. time interval. As seen in Figure B3, for a constant error, the frequency change was a ramp, which ran toward lower frequencies for "positive" errors to be reduced. The opposite was true for "negative" errors. If the error was varying with time, the shape of the frequency change was not, in general, a ramp. For example, the latter part of the sample error, which was a ramp, produced a parabolic frequency change. This effect was minimized, however, by the fact that the integration time was short and that normal errors were of relatively low frequency.

These two error signals were time shared in the display as shown at the bottom of the example in Figure B3. One channel prevailed for . 25 sec. follwed by a . 75 sec. period for the other channel.

Roll angle error was displayed by means of a binaural cue. For example, if the roll error was "negative", the auditory display would be louder in the right ear commanding a correction to the right. Sound pressure level readings are shown in Figure B5, for various roll angle errors.

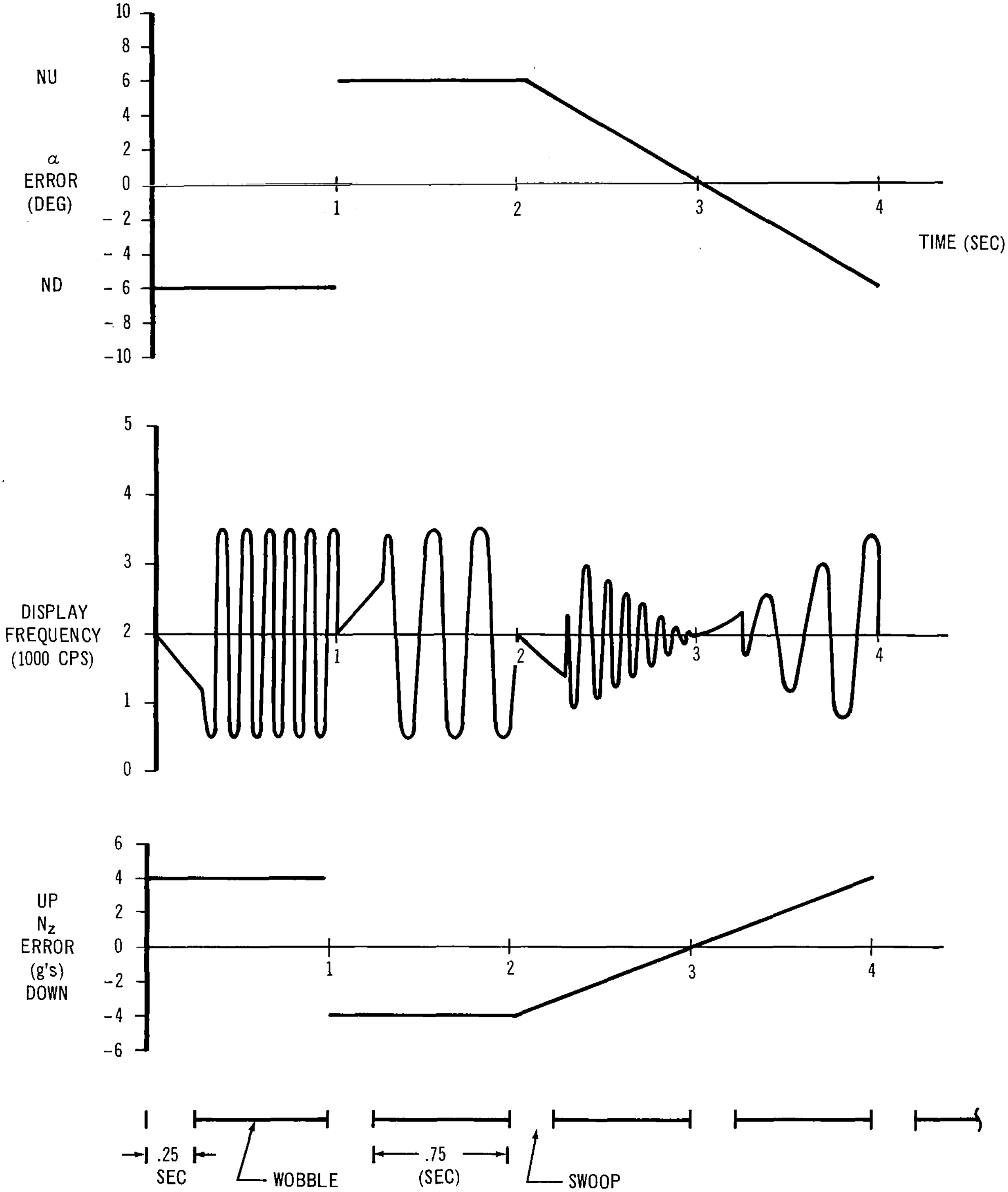


Figure B3: Sample Input-Output of Acoustic Display Used in Selection Phase

The mechanization which produced this auditory display is seen in Figure B6. The V.C.O. obtained its input from a summing amplifier which was used to sum the various changes in voltage. The center frequency (2000 c.p.s.) was formed by summing in a constant voltage shown as a pot connected to a reference voltage.

The "wobble" or sinusoidal frequency change was produced by using the error signal to modulate either a 4 c.p.s. or 11 c.p.s. carrier frequency. This modulation was accomplished by using two analog multipliers (see Figure B6). The error signal was sent through diodes so that the correct sign of error modulated the proper frequency carrier.

The "swoop" or integrated frequency change was formed by simply integrating the error for .25 sec. and sending it through the summer to the V.C.O. (See Figure B6.)

The signal which was sent to the binaural generator was shaped to have a gain curve which was the square root of the roll angle error. This was done so that the change in volume for a given error would be greatest around zero. (See Figures B4, B5, and B6.)

Provisions were made to employ either of the frequency modulation channels to display angle of attack and to display load factor.

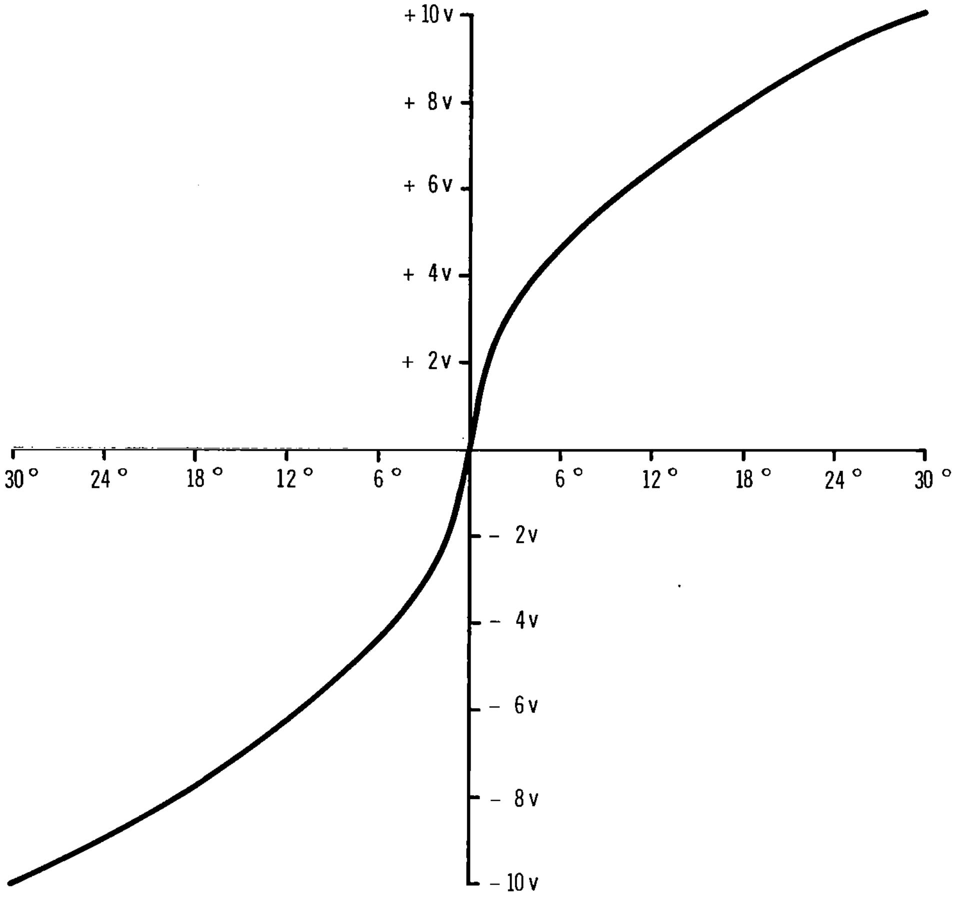
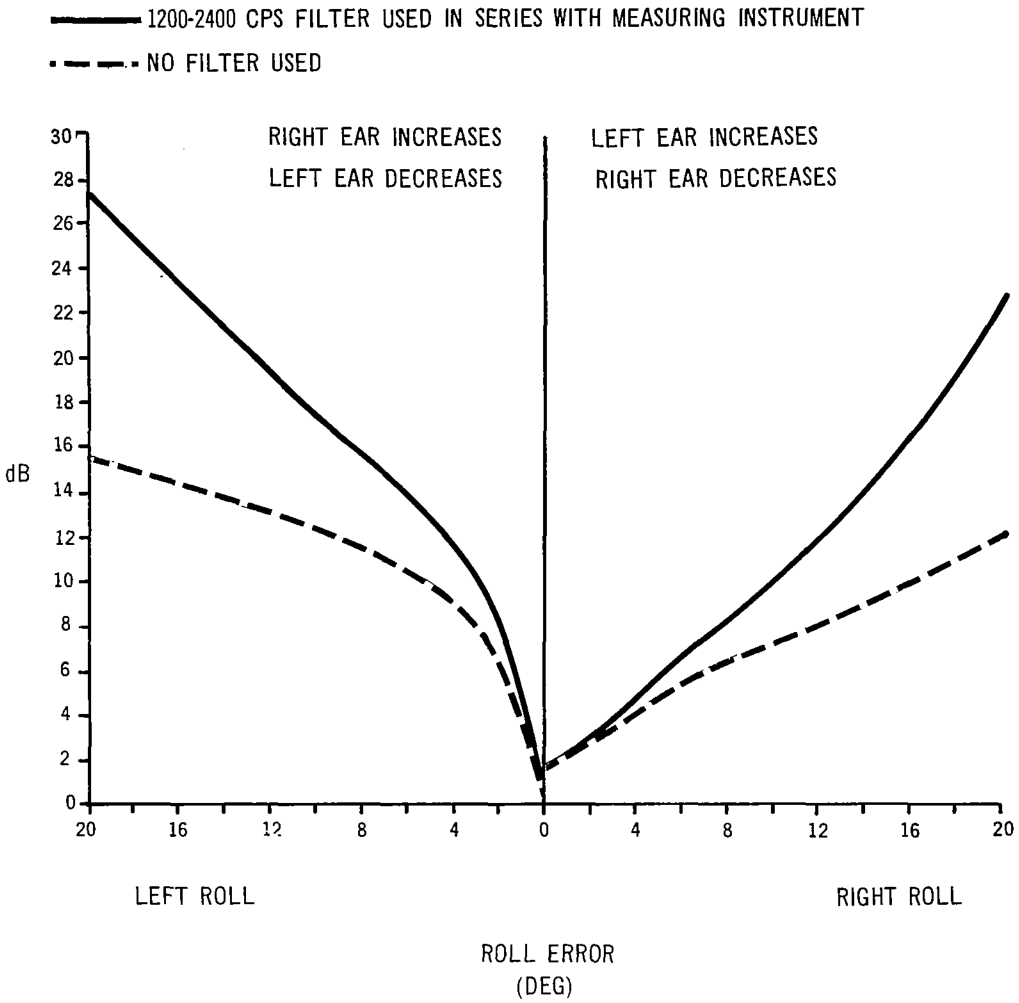


Figure B4: Roll Threshold Transfer Function (Square Root) Used in Selection Phase



SOUND PRESSURE LEVEL DIFFERENTIAL BETWEEN
LEFT AND RIGHT EARS FOR ROLL ANGLES SHOWN

0 db ON PLOT IS EQUAL TO APPROXIMATELY
88 db SPL [db REFFERENCED TO .0002 DYNES/CM^2]

Figure B5: Actual Binaural Sound Level Difference as a Function of Roll Angle Error

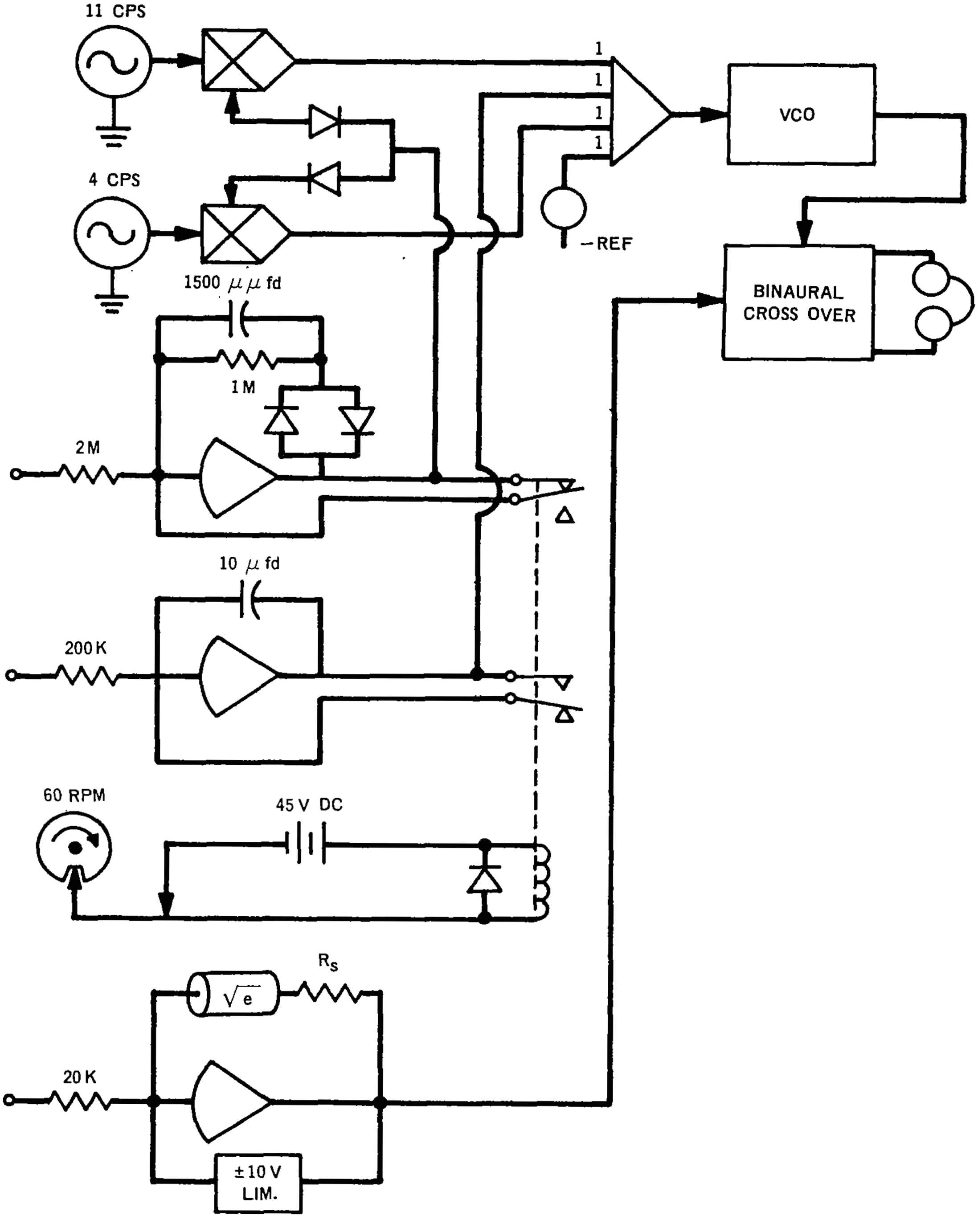


Figure B6: Mechanization for Acoustic Channels Used in Display Selection Phase

APPENDIX C

APPARATUS USED IN ACOUSTIC DISPLAY SELECTION PHASE

During the second experimental phase of this program a mock-up of the actual X-15 cockpit was constructed. Flight controls were accurately reproduced both mechanically and with respect to proper load-deflection characteristics. The instrument panel was provided only with the three instruments selected for study during this phase: a roll angle indicator, an angle of attack indicator, and a normal acceleration indicator. All three instruments were specially constructed to display, by separate but concentric pointers, both a command signal and a situation signal. These instruments were made using 90 degree meter movements as a consequence of which slight changes in dial scaling were required, relative to standard instruments, to compress flight profile indications into the constricted display range.

The control side stick was a replica of the stick used in the actual X-15 aircraft. Force displacement curves for pitch and roll axes were taken from NASA TN D-1402 and accurately reproduced through the use of bungees and suitable levering to the stick. A trim knob was provided which consisted of a linear pot which reset the null point in the computer. Stick position was sensed by geared single turn potentiometers which provided an analog signal for the computer. The experimental subject was provided with a set of sterophonic headphones for audio cues and intercom. In addition, a verbal communications task was provided and presented through the same audio system. A four channel mixer and amplifier provided complete control over all audio presentations to the subject.

A typical experimental run proceeded as follows: The subject was seated in the cockpit with all instruments indicating initial conditions and audio indicating zero error. When the experimenter pushed the start button, the computer switched into OPERATE and presented a command signal on the command pointer of the visual instruments and on the acoustic displays, as programmed for the flight profile. Flight conditions were visually indicated on the second pointer of the visual instruments. Auditory error signals were simultaneously generated for acoustically displayed parameters and were presented to the subject. Verbal communication messages were mixed with the auditory tracking information and required a response by the subject on the four-position switch at his left.

Response times for verbal communications were recorded on an automatic timer, while response positions were recorded on a chart recorder. The same chart recorder was used to continuously record accumulated subject flight profile error. Each complete 5 minute experimental run was divided into 6 sub-sections representing different flight profile conditions (see Appendix D), and error scores were accumulated over each individual section. At the end of a 5 minute run the computer automatically reset, the verbal communications tape stoped and initial conditions were automatically reset completing preparations for the next run.

The experimenter's control console provided for selection of the parameter(s) to be commanded acoustically. It also provided for assignment of acoustic channels to parameters in the cases of angle of attack and normal acceleration. When a parameter was displayed acoustically, the corresponding visual instrument was covered. When a parameter was displayed visually, it was not displayed acoustically.

APPENDIX D

COMMANDED PROFILE USED IN ACOUSTIC DISPLAY SELECTION PHASE

The "flight" profile generated by the command profile is shown in Fig. D1. It was based upon six phases of an X-15 flight as follows:

1. Initial rotation and beginning of trajectory: 0-40 sec.
2. Climbing under full rocket power with slight heading maneuver: 40-80 sec.
3. Completion of powered phase, start of ballistic coasting and completion of heading change: 80-120 sec.
4. Ballistic phase in rare atmosphere (no aerodynamic forces), rolling maneuver with reaction controls and setting up of recovery angle of attack: 120-200 sec.
5. Recovery phase, high g's and high aerodynamic pressure: 200-260 sec.
6. Start of deceleration glide and heading correction: 260-300 sec.

The profile described here was designed to provide subjects with a five minute tracking task with display and control requirements similar to those in the X-15.

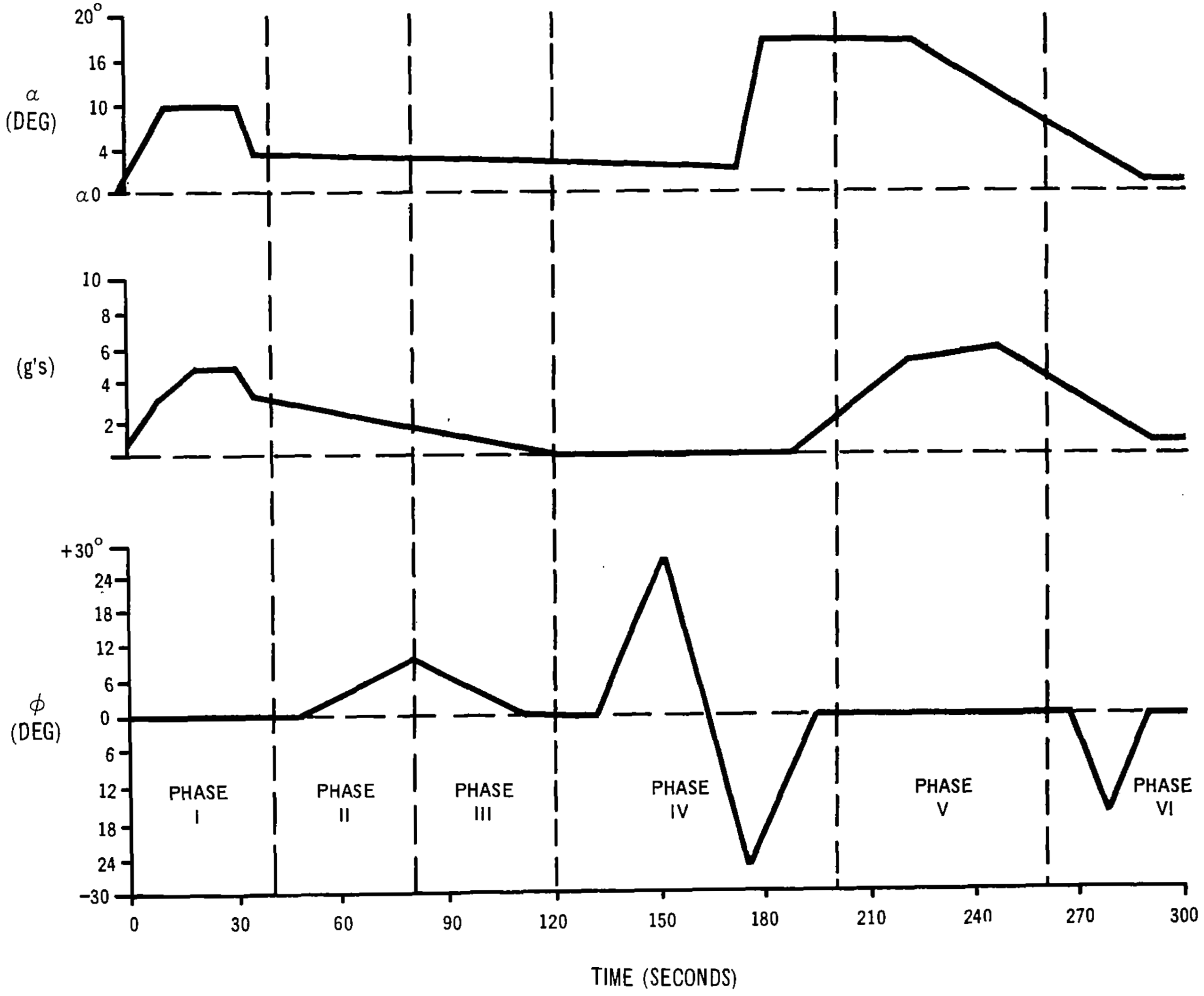


Figure D1: Command Profile Used in Acoustic Display Selection Phase

APPENDIX E

VERBAL MESSAGE TAPES FOR ACOUSTIC DISPLAY SELECTION PHASE

MESSAGE NUMBER

TAPE NUMBER		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	(Switch Position) Message	1	3	1	1	3	2	3	2	4	4	4	2	2	3	4	1
	TIME (Seconds)	5	25	50	60	85	105	115	135	165	175	185	220	230	250	275	285
2	(Switch Position) Message	4	4	1	2	4	3	2	1	3	1	1	3	3	2	2	4
	TIME (Seconds)	10	20	55	65	95	105	115	140	150	165	180	210	220	245	275	290
3	(Switch Position) Message	3	1	2	1	3	3	2	2	4	4	3	2	1	4	1	4
	TIME (Seconds)	25	35	50	65	85	100	110	125	160	170	190	205	225	240	265	280
4	(Switch Position) Message	1	3	3	1	2	1	3	2	4	4	1	3	4	2	2	4
	TIME (Seconds)	20	30	45	60	90	100	110	140	155	165	175	210	240	250	270	290
5	(Switch Position) Message	2	1	3	2	1	4	3	3	4	1	1	2	4	2	3	4
	TIME (Seconds)	15	30	45	55	85	100	115	130	145	155	190	215	225	255	265	285
6	(Switch Position) Message	3	1	2	1	2	1	4	2	4	4	2	3	4	3	1	3
	TIME (Seconds)	10	25	60	75	90	105	115	125	150	160	180	205	220	245	275	295
7	(Switch Position) Message	2	4	4	1	1	2	1	3	2	2	4	3	4	1	3	3
	TIME (Seconds)	25	35	45	70	90	105	115	140	155	170	195	210	225	235	280	290
8	(Switch Position) Message	1	3	4	4	2	4	3	4	2	2	1	3	3	1	1	2
	TIME (Seconds)	15	35	45	65	95	110	115	130	140	150	185	205	215	255	265	295
9	(Switch Position) Message	2	2	4	4	1	1	4	2	1	3	4	1	3	3	2	3
	TIME (Seconds)	5	20	45	60	75	85	100	125	140	165	190	215	230	250	265	275
10	(Switch Position) Message	3	3	2	4	2	1	2	3	4	4	1	3	4	2	1	1
	TIME (Seconds)	25	35	50	65	85	110	115	130	155	170	195	210	225	255	270	285
11	(Switch Position) Message	4	2	1	2	4	4	3	3	2	2	3	1	4	1	1	3
	TIME (Seconds)	10	35	55	70	90	100	110	135	150	170	190	205	230	240	265	290
12	(Switch Position) Message	2	1	4	3	3	3	2	3	1	2	4	1	4	1	2	4
	TIME (Seconds)	15	25	45	70	85	105	115	125	155	170	185	205	225	245	265	280

APPENDIX F

ANALYSES AND SUMMARIES OF DATA FROM TRIALS ONE AND TWO OF THE ACOUSTIC DISPLAY SELECTION PHASE

Analyses and summaries of data from the acoustic display selection phase of the program supplementary to those presented in the text, are presented below. The format is the same as that employed in the text.

TABLE F1: ANALYSIS OF VARIANCE SUMMARY TABLE FOR THREE PERFORMANCE MEASURES: ONE ACOUSTIC CHANNEL, FIRST TRIAL

Source of Variation	df	Integral of Absolute Error in Angle of Attack		Integral of Absolute Error in Normal Acceleration		Integral of Absolute Error in Roll Angle	
		MS	F	MS	F	MS	F
Channel-Parameter Assignment (C-P)	1	.231	.627	.006	.030	.038	.105
Display (D)	3	3.089	7.503**	.593	2.568	2.100	12.083***
Flight Phase (P)	5	2.309	19.024***	2.418	41.293***	.338	9.559***
(C-P) x D	3	.223	.542	.004	.016	.193	1.113
(C-P) x P	5	.065	.538	.059	1.015	.019	.526
D x P	15	.693	7.776***	.131	1.440	.063	2.494**
(C-P) x D x P	15	.110	1.236	.112	1.221	.015	.582

* $p < .05$
** $p < .01$
*** $p < .001$

TABLE F2: MEAN PERFORMANCE ON THREE PERFORMANCE MEASURES, ONE ACOUSTIC CHANNEL, FIRST TRIAL

Channel Parameter Assignment / Display	α Acoustic	ϕ Acoustic	g Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.798	.377	.464	.433	.518
α - Swoop g - Wobble ϕ - Binaural	1.066	.414	.426	.443	.587
Total	.932	.396	.445	.438	.553

A. INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK

Channel Parameter Assignment / Display	α Acoustic	ϕ Acoustic	g Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.540	.310	.343	.344	.384
α - Swoop g - Wobble ϕ - Binaural	.545	.279	.323	.348	.374
Total	.543	.295	.333	.346	.379

B. INTEGRAL OF ABSOLUTE ERROR IN NORMAL ACCELERATION

Channel Parameter Assignment Display	α Acoustic	ϕ Acoustic	g Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.242	.728	.179	.170	.330
α - Swoop g - Wobble ϕ - Binaural	.314	.515	.210	.167	.302
Total	.278	.621	.194	.169	.316

C. INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE

TABLE F3: ANALYSIS OF VARIANCE SUMMARY TABLE FOR THREE PERFORMANCE MEASURES: TWO ACOUSTIC CHANNELS, FIRST TRIAL

Source of Variation	df	Integral of Absolute Error in Angle of Attack		Integral of Absolute Error in Normal Acceleration		Integral of Absolute Error in Roll Angle	
		MS	F	MS	F	MS	F
Channel-Parameter Assignment (C-P)	1	8.123	8.852*	2.617	5.496	1.292	15.771**
Display (D)	3	4.118	7.199**	1.269	5.319**	1.268	74.949***
Flight Phase (P)	5	3.857	8.876***	1.239	9.399***	.253	11.465***
(C-P) x D	3	2.443	4.270*	.977	4.094*	.204	12.051***
(C-P) x P	5	.413	.951	.432	3.277*	.030	1.375
D x P	15	.765	3.620***	.182	1.824	.029	1.597
(C-P) x D x P	15	.177	.839	.144	1.435	.023	1.290

* $p < .05$
** $p < .01$
*** $p < .001$

TABLE F4: MEAN PERFORMANCE ON THREE PERFORMANCE MEASURES, TWO ACOUSTIC CHANNELS, FIRST TRIAL

Channel Parameter Assignment Display	$\alpha + \phi$ Acoustic	$\phi + g$ Acoustic	$\alpha + g$ Acoustic	All Visual	Total
α -Wobble g -Swoop ϕ -Binaural	.526	.316	.414	.273	.382
α -Swoop g -Wobble ϕ -Binaural	.898	.376	1.474	.428	.794
Total	.712	.346	.944	.350	.588

A. INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK

Channel Parameter Assignment Display	$\alpha + \phi$ Acoustic	$\phi + g$ Acoustic	$\alpha + g$ Acoustic	All Visual	Total
α -Wobble g -Swoop ϕ -Binaural	.274	.215	.256	.191	.234
α -Swoop g -Wobble ϕ -Binaural	.400	.255	.914	.301	.468
Total	.337	.235	.585	.246	.351

B. INTEGRAL OF ABSOLUTE ERROR IN NORMAL ACCELERATION

Channel Parameter Assignment / Display	$\alpha + \phi$ Acoustic	ϕ + g Acoustic	α + g Acoustic	All Visual	Total
α -Wobble g -Swoop ϕ -Binaural	.292	.314	.128	.110	.211
α -Swoop g -Wobble ϕ -Binaural	.640	.481	.197	.183	.375
Total	.466	.397	.163	.147	.293

C. INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE

TABLE F5: ANALYSIS OF VARIANCE SUMMARY TABLE FOR THREE PERFORMANCE MEASURES: THREE ACOUSTIC CHANNELS, FIRST TRIAL

Source of Variation	df	Integral of Absolute Error in Angle of Attack		Integral of Absolute Error in Normal Acceleration		Integral of Absolute Error in Roll Angle	
		MS	F	MS	F	MS	F
Channel-Parameter Assignment (C-P)	1	7.205	8.294*	2.316	3.437	.004	.037
Display (D)	1	6.373	6.318*	2.055	3.201	2.368	27.309**
Flight Phase (P)	5	.947	5.605***	.830	4.354**	.046	1.991
(C-P) x D	1	3.366	3.337	1.050	1.636	.053	.613
(C-P) x P	5	.293	1.734	.251	1.315	.011	.490
D x P	5	.391	2.846*	.215	1.506	.017	.832
(C-P) x D x P	5	.208	1.512	.113	.791	.017	.816

* $p < .05$
** $p < .01$
*** $p < .001$

TABLE F6: MEAN PERFORMANCE ON THREE PERFORMANCE MEASURES, THREE ACOUSTIC CHANNELS, FIRST TRIAL

Channel Parameter Assignment Display	All Acoustic	All Visual	Total
α-Wobble g-Swoop ϕ-Binaural	.377	.236	.306
α-Swoop g-Wobble ϕ-Binaural	1.299	.409	.854
Total	.838	.323	.580

A. INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK

Channel Parameter Assignment Display	All Acoustic	All Visual	Total
α-Wobble g-Swoop ϕ-Binaural	.257	.174	.216
α-Swoop g-Wobble ϕ-Binaural	.777	.275	.526
Total	.517	.225	.371

B. INTEGRAL OF ABSOLUTE ERROR IN NORMAL ACCELERATION

Channel Parameter Assignment Display	All Acoustic	All Visual	Total
α-Wobble g-Swoop ϕ-Binaural	.456	.095	.276
α-Swoop g-Wobble ϕ-Binaural	.422	.155	.288
Total	.439	.125	.332

C. INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE

TABLE F7: ANALYSIS OF VARIANCE SUMMARY TABLE FOR THREE PERFORMANCE MEASURES: ONE ACOUSTIC CHANNEL, SECOND TRIAL

Source of Variation	df	Integral of Absolute Error in Angle of Attack		Integral of Absolute Error in Normal Acceleration		Integral of Absolute Error in Roll Angle	
		MS	F	MS	F	MS	F
Channel-Parameter Assignment (C-P)	1	.695	1.021	.006	.013	.131	.745
Display (D)	3	2.252	8.736***	.350	2.514	.749	3.474
Flight Phase (P)	5	2.364	11.853***	2.817	14.625***	.211	5.270**
(C-P) x D	3	.202	.784	.141	1.017	.007	.034
(C-P) x P	5	.384	1.924	.063	.330	.017	.435
D x P	15	.709	6.377***	.145	1.630	.022	.903
(C-P) x D x P	15	.117	1.049	.080	.900	.011	.433

* $p < .05$
** $p < .01$
*** $p < .001$

TABLE F8: MEAN PERFORMANCE ON THREE PERFORMANCE MEASURES, ONE ACOUSTIC CHANNEL, SECOND TRIAL

Channel Parameter Assignment Display	α Acoustic	ϕ Acoustic	g Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.764	.512	.411	.327	.504
α - Swoop g - Wobble ϕ - Binaural	1.007	.486	.461	.541	.624
Total	.885	.499	.436	.434	.564

A. INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK

Channel Parameter Assignment Display	α Acoustic	ϕ Acoustic	g Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.458	.517	.289	.292	.389
α - Swoop g - Wobble ϕ - Binaural	.483	.357	.281	.389	.378
Total	.470	.437	.285	.341	.384

B. INTEGRAL OF ABSOLUTE ERROR IN NORMAL ACCELERATION

Channel Parameter Assignment / Display	α Acoustic	ϕ Acoustic	g Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.290	.448	.153	.167	.264
α - Swoop g - Wobble ϕ - Binaural	.329	.472	.230	.236	.317
Total	.309	.460	.191	.202	.291

C. INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE

TABLE F9: ANALYSIS OF VARIANCE SUMMARY TABLE FOR THREE PERFORMANCE MEASURES: TWO ACOUSTIC CHANNELS, SECOND TRIAL

Source of Variation	df	Integral of Absolute Error in Angle of Attack		Integral of Absolute Error in Normal Acceleration		Integral of Absolute Error in Roll Angle	
		MS	F	MS	F	MS	F
Channel-Parameter Assignment (C-P)	1	3.5546	2.256	.833	1.386	.024	.344
Display (D)	3	2.987	5.213**	.680	1.873	1.159	53.160***
Flight Phase (P)	5	3.445	8.899***	1.190	11.174***	.236	10.981***
(C-P) x D	3	.615	1.074	.212	.583	.004	.191
(C-P) x P	5	.578	1.494	.125	1.178	.009	.397
D x P	15	.612	4.400***	.092	1.532	.021	1.324
(C-P) x D x P	15	.127	.915	.046	.773	.007	.436

* $p < .05$
** $p < .01$
*** $p < .001$

TABLE F10: MEAN PERFORMANCE ON THREE PERFORMANCE MEASURES, TWO ACOUSTIC CHANNELS, SECOND TRIAL

Channel Parameter Assignment Display	$\alpha + \phi$ Acoustic	$\phi + g$ Acoustic	$\alpha + g$ Acoustic	All Visual	Total
α -Wobble g -Swoop ϕ -Binaural	.520	.278	.546	.313	.414
α -Swoop g -Wobble ϕ -Binaural	.903	.381	1.083	.377	.686
Total	.712	.330	.815	.345	.550

A. INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK

Channel Parameter Assignment Display	$\alpha + \phi$ Acoustic	$\phi + g$ Acoustic	$\alpha + g$ Acoustic	All Visual	Total
α -Wobble g -Swoop ϕ -Binaural	.275	.204	.318	.217	.254
α -Swoop g -Wobble ϕ -Binaural	.435	.215	.625	.266	.385
Total	.355	.210	.472	.242	.320

B. INTEGRAL OF ABSOLUTE ERROR IN NORMAL ACCELERATION

Channel Parameter Assignment / Display	$\alpha + \phi$ Acoustic	$\phi + g$ Acoustic	$\alpha + g$ Acoustic	All Visual	Total
α - Wobble g - Swoop ϕ - Binaural	.451	.331	.130	.112	.256
α - Swoop g - Wobble ϕ - Binaural	.447	.356	.162	.149	.278
Total	.449	.344	.146	.130	.267

C. INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE

TABLE F11: ANALYSIS OF VARIANCE SUMMARY TABLE FOR THREE PERFORMANCE MEASURES: THREE ACOUSTIC CHANNELS, SECOND TRIAL

Source of Variation	df	Integral of Absolute Error in Angle of Attack		Integral of Absolute Error in Normal Acceleration		Integral of Absolute Error in Roll Angle	
		MS	F	MS	F	MS	F
Channel-Parameter Assignment (C-P)	1	2.073	8.556*	.511	3.107	.090	8.604*
Display (D)	1	1.846	10.767*	.356	3.236	1.727	130.618***
Flight Phase (P)	5	.962	17.742***	.451	7.825***	.049	3.523*
(C-P) x D	1	.482	2.814	.024	.216	.005	.355
(C-P) x P	5	.528	9.740***	.055	.951	.006	.404
D x P	5	.388	6.425***	.033	.774	.021	1.763
(C-P) x D x P	5	.404	6.699***	.033	.774	.013	1.098

* p <.05
** p <.01
*** p <.001

TABLE F12: MEAN PERFORMANCE ON THREE PERFORMANCE MEASURES, THREE ACOUSTIC CHANNELS, SECOND TRIAL

Channel Parameter Assignment / Display	All Acoustic	All Visual	Total
α-Wobble g-Swoop ϕ-Binaural	.365	.230	.298
α-Swoop g-Wobble ϕ-Binaural	.801	.382	.591
Total	.583	.306	.445

A. INTEGRAL OF ABSOLUTE ERROR IN ANGLE OF ATTACK

Channel Parameter Assignment / Display	All Acoustic	All Visual	Total
α-Wobble g-Swoop ϕ-Binaural	.251	.161	.206
α-Swoop g-Wobble ϕ-Binaural	.429	.275	.352
Total	.340	.218	.279

B. INTEGRAL OF ABSOLUTE ERROR IN NORMAL ACCELERATION

Channel Parameter Assignment / Display	All Acoustic	All Visual	Total
α-Wobble g-Swoop ϕ-Binaural	.346	.091	.218
α-Swoop g-Wobble ϕ-Binaural	.421	.138	.280
Total	.383	.115	.249

C. INTEGRAL OF ABSOLUTE ERROR IN ROLL ANGLE

APPENDIX G

SAMPLE OF QUESTIONNAIRE USED IN ACOUSTIC DISPLAY SELECTION PHASE

Name: ______________________ Date: __________ Time: _________

Number of hours flown: ________

Types of aircraft flown: ________

QUESTIONNAIRE

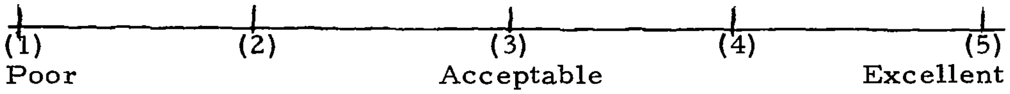
NASA-ACOUSTIC DISPLAY

In answering the following questions consider a point of view to the exclusion of yourself. Many display characteristics still defy reduction to measurable criteria and much weight must be given to your opinions. With these thoughts in mind, try to temper your answers with the highest degree of objectivity. Try not to gloss over any questions for in doing so you may relegate a poor display characteristic to a measure of non-importance.

In a few of the questions below there is provided a rating scale. You are to rank the various configurations above that part of the scale which is most descriptive of your point of view. If you feel you must comment on any such question, feel free to do so. Use the following corresponding symbols:

Angle of Attack and Roll (Acoustic) = A
Roll and Acceleration (Acoustic) = B
Angle of Attack and Acceleration (Acoustic) = C
All Visual = D

EXAMPLE:



Comments:

1. Rank the display combinations in order of usefulness.

(1) (2) (3) (4) (5)
Least Useful Neutral Most Useful

Comments:

2. Rank the display combinations in order of the degree of work required.

(1) (2) (3) (4) (5)
Null Neutral Excessive

Comments:

3. Indicate the degree to which you feel you could increase your performance (e.g., a lot, a little) with practice.

A ____________________ C ____________________

B ____________________ D ____________________

4. For each condition what do you think could be improved?

A.

B.

C.

D.

5. Please make any additional comment you have.

APPENDIX H

ACOUSTIC DISPLAYS USED IN THE ACOUSTIC DISPLAY EVALUATION PHASE

The acoustic displays employed in the acoustic display evaluation phase of the program were modifications of some of the displays used in the previous phase. They differed from the previous displays (See Appendix B) in the following respects:

1. The output equation for the V. C. O. was:

   frequency (in c. p. s.) = 185 x (D. C. voltage level)

2. The center frequency of the V. C. O. was changed from 2000 c. p. s. to 500 c. p. s.

3. Angle of attack error was displayed by a modified "wobble" display. The modification consisted of changing the carrier for the down error (or up command) signal from an 11 c. p. s. sinusoid to a 10 c. p. s. square wave, which did not go below zero. In other words, the carrier had only one sign. This means that the frequency variation went from the center frequency to a higher frequency only. (See Figure H1.)

4. Because only one longitudinal parameter was displayed, there was no need for time sharing of signal. The signal was interrupted, however, in order to reduce habituation and increase discriminability of the binaural cue. For this purpose, an interrupter was arranged so that the display was off for . 6 sec. and on for . 6 sec. (See Figures H1 and H3.)

5. The gain shaping into the binaural generator was changed from the square root function to a function which produced a much higher gain change around zero. A voltage plot of this function is shown in Figure H2. This can be compared with that in the acoustic display selection phase. (See Figure B4).

This new gain function was obtained experimentally to satisfy the criterion that the pilot was able to detect a $.5^{\circ}$ change in error for the first 1.5° of deviation in either direction and could detect a 1° change in error between 1.5° and 5° of error in either direction.

The mechanization of the auditory display generator is shown in Figure H3. Its function is very similar to that of the display generator used in the previous phase (Appendix B) except for the changes noted. The changes in circuitry can be seen by comparing Figure H3 with Figure B6.

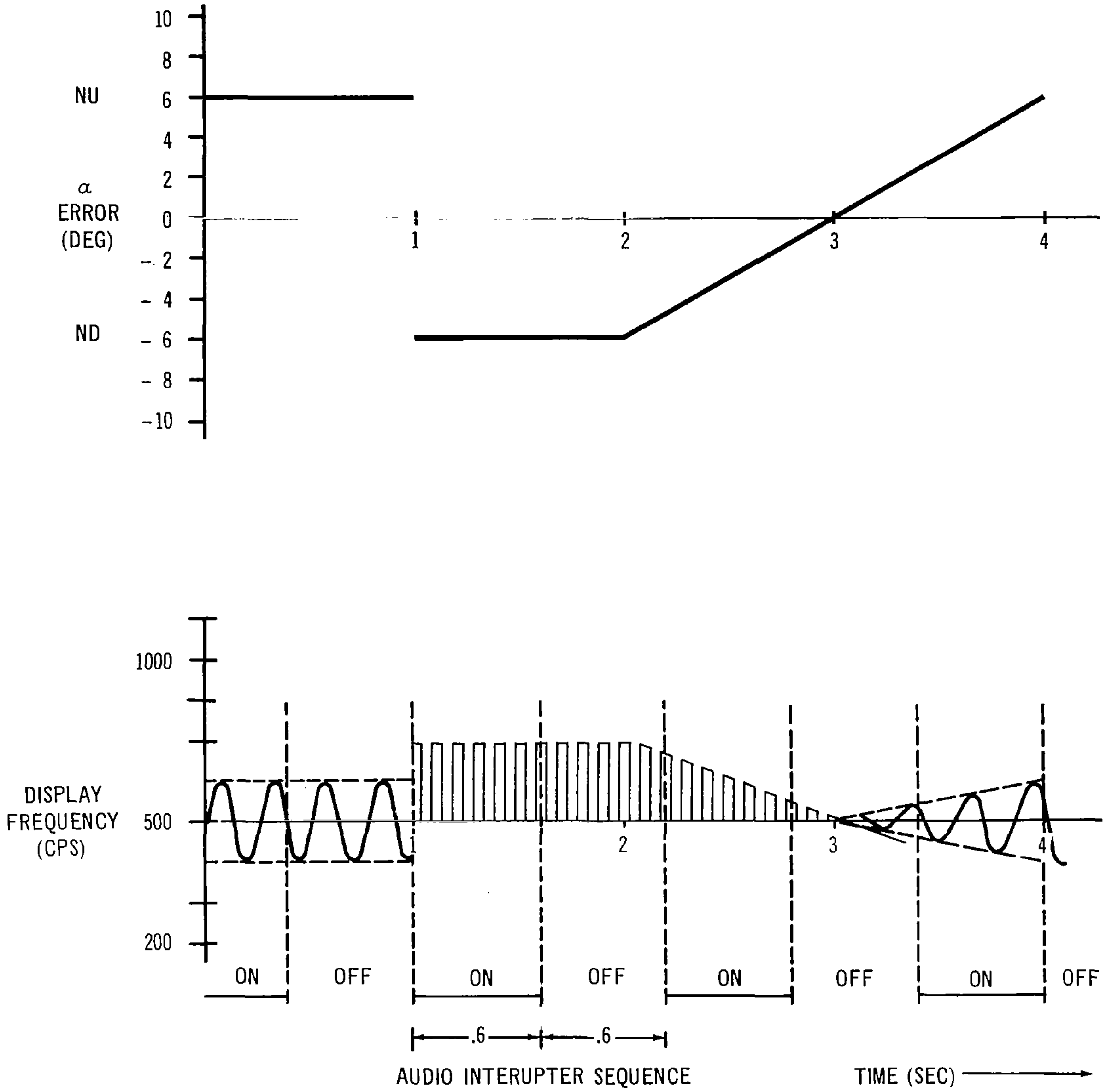


Figure H1: Sample Input-Output of Acoustic Display Used in Evaluation Phase

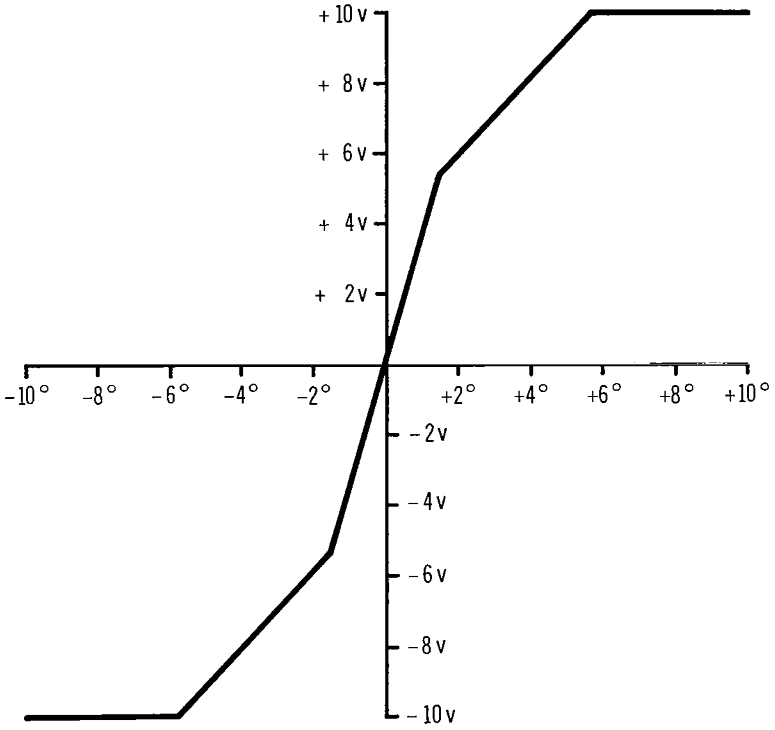


Figure H2: Roll Threshold Transfer Function Used in Evaluation Phase

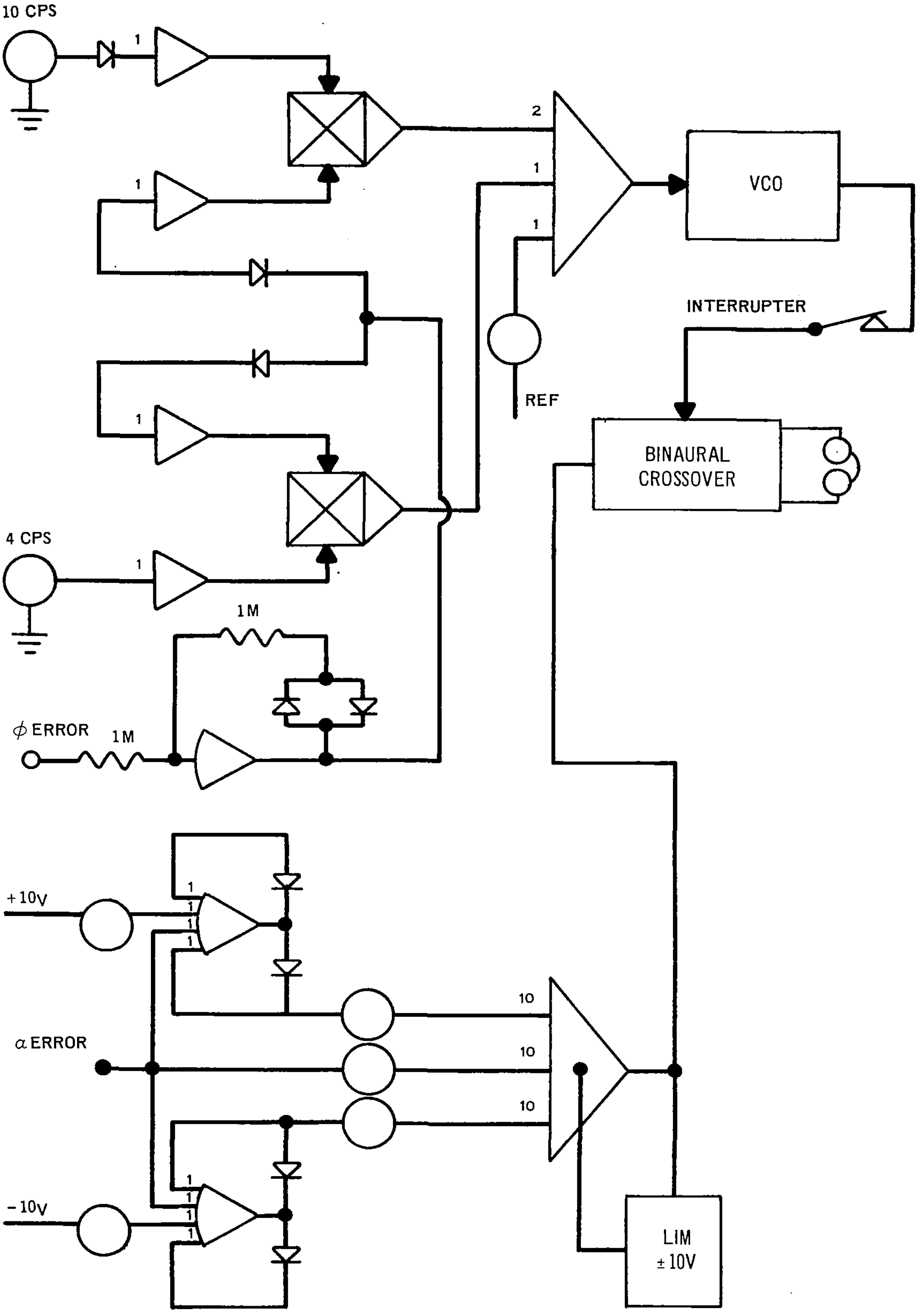


Figure H3: Mechanization for Acoustic Channels Used in Display Evaluation Phase

APPENDIX I

"AUGMENTATION" OF DISPLAYS

The term "augmentation", as used here, means displaying a variable which is a linear combination of a parameter and its first and second derivatives with respect to time. This is a restricted concept relative to one in which arbitrary functions of a parameter and its derivatives (and anti-derivatives) with respect to time would be displayed.

In the acoustic display evaluation phase of the current program, roll angle and angle of attack displays were "augmented" for some experimental conditions. The factors (coefficients) used in the augmentation resulted from examination of the literature and from small sample empirical studies performed on the simulator. The factors used are shown on the analog circuits for longitudinal dynamics (Figure K2) and for lateral directional dynamics (Figure K3).

APPENDIX J

EXPERIMENTER'S CONSOLE AND SIMULATED COCKPIT USED IN ACOUSTIC DISPLAY EVALUATION PHASE

A simulated X-15 cockpit was constructed incorporating all controls and instruments required for performance of a primary flying task. Instruments not directly necessary for a primary flight task, such as engine parameter instruments and warning and indicator lights, were simulated by photographic decals. Each instrument and control is described below with reference to function, control signal and special construction features. The simulation system is presented schematically in Figure J1.

CONTROL SIDE STICK AND RUDDER

An accurate full scale model of the X-15 control side stick was made because actual hardware was unavailable. Due to the necessity of providing electrical control signals for computer operation, a frame was built to accept position feedback potentiometers in both roll and longitudinal axes. All pivot axis dimensions and mounting dimensions were maintained from the actual stick and force displacement characteristics were reproduced from curves taken from NASA Tech. Note No. D-1402. The standard control grip was reproduced in cast epoxy and incorporated a pilot's microphone switch and pitch trim control. Two variations of pitch trim actuation were examined. The first was an attempt at simplification of the trim system and used the trim potentiometer parallel to the pitch feedback position potentiometer. No attempt to mechanically reposition the control stick was made. Due to adverse subject-pilot reaction, the trim system finally adopted was in principle similar to that used in the X-15 aircraft. A servo-amplifier driven 28V DC motor driving, through a multi-stage spur and worm gear reduction unit, served to drive the control stick to the trim-wheel indicated position. Extreme trim positions were -20° and +5° surface deflection and maximum trim slew rate was 25° in 1.7 seconds. The roll force bungee gave linear force displacement characteristics to a maximum of lb. force at a 3 in. handle pivot radius. The pitch force bungee gave a maximum force of approximately 28 lbs. at 4.25 in. radius. Both roll and pitch stick positions were sensed by single turn wire wound 5K ohm potentiometers appropriately geared to give 300° of rotation for maximum deflection of the control stick. Rudder position signals were similarly derived through a 300° potentiometer pulley driven from a rudder linkage cable.

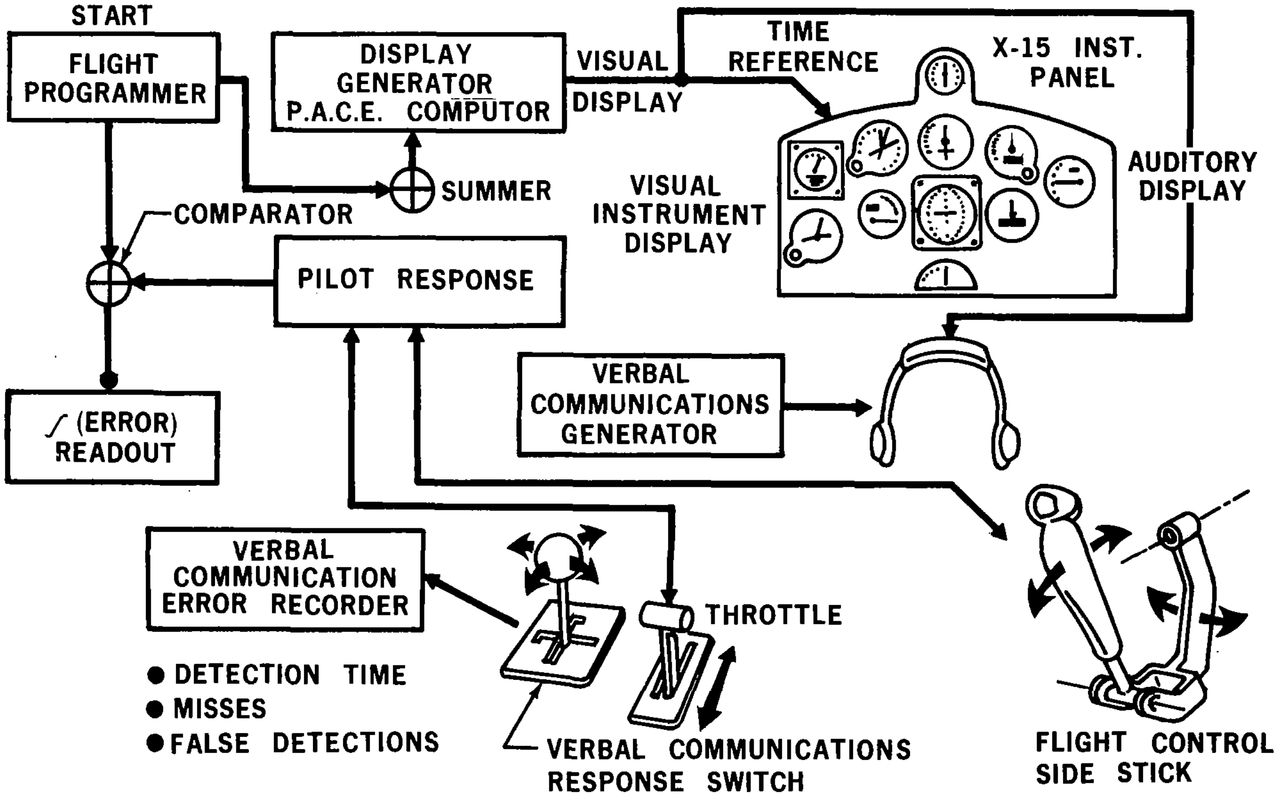


Figure J1: Schematic Representation of the Simulation System Used in the Acoustic Display Evaluation Phase

THROTTLE CONTROL

The throttle control was built in conjunction with a start mechanism for the flight time stop watch. Throttle position was sensed in two ways: as the throttle lever was moved sideways about an axial pivot axis, a switch closed and a 50% throttle signal was applied to the computer. At the same time a second micro-switch closed a relay, momentarily pulsing a solenoid and starting the "Elapsed Time" watch on the instrument panel. As the throttle handle was moved forward about a lateral pivot axis, an appropriately geared potentiometer applied the 50 - 100% power signal to the flight dynamics computer.

MISSION ELAPSED TIME TIMER

A Minerva Model 125 interval timer was displayed at the top and middle of the instrument panel. A 110V AC solenoid operated through a lever system directly on the Start-Stop-Reset button of the watch. To minimize the possibility of shock damage to the watch, and to silence the mechanism, a shock absorbant spring was mounted between the solenoid and cocking lever. In addition, the mounting frame and all moving parts were isolated from the instrument panel through sheet rubber padding. Since it was desirable to start the watch with a momentary depression of the start crown, a pulse circuit was incorporated to deliver a .05 second pulse to the solenoid as the throttle lever was moved from the "Power Off" position. No pulse was delivered as the throttle was returned to the "Power Off" position at the end of engine power so that the watch indicated mission elapsed time from initial Power On.

VERBAL COMMUNICATIONS TASK RESPONSE SWITCH

Located on the left console aft of the throttle lever was a four position switch to indicate the subject's responses in the verbal comprehension task. Responses by the subject, through movement of the switch in any one of four positions, were indicated on a chart recorder by one of four voltage levels. A magnetic tape recording of the verbal messages (see Appendix L) was played through the subject-pilot's audio system and recorded, along with the subject's responses, on the chart recorder. Comparison of task and response pulses thus indicated subject performance.

AIR SPEED INDICATOR

The Air Speed Indicator was not used during the simulation, as a result of the high altitude involved. A 270° 50 μa metermovement with a non-linear shaping network, to simulate the actual instrument, was incorporated, however. This was done in order to have an operational instrument available in the event that it was decided to simulate X-15 landings or other low-altitude maneuvers.

PRESSURE ALTITUDE INDICATOR

The pressure altitude indicator was not used during the simulation. An operational instrument, however, was constructed in order to be able to simulate landings and other low-altitude maneuvers, if desired. An MS28044 Military Standard Pressure Altimeter was modified by mounting a Mark 22 110V 400 synchro-receiver to drive the 100 ft. indicating needle directly. A Mark 22 synchro transmitter was driven by a 10 turn servo unit through a 4.9 6:1 step-up gear box to provide a maximum reading of 49,600 ft. on the altimeter for maximum signal input.

ACCELERATION INDICATOR

Vertical acceleration was one of the experimentally displayed parameters in the earlier display selection phase. As a result, the specially constructed instrument used in that phase (see Appendix C), a dual indicating micro-ammeter movement capable of showing parameters and commands on the same scale by two different needles, was available. The command needle was biased out of the view area permitting use of the instrument as a standard g meter.

ANGLE OF ATTACK INDICATOR

Angle of attack was an experimentally displayed parameter in this phase and hence a command visual display was used (see Appendix C). The command needle could be biased out of view, permitting use of the instrument as a standard instrument. The meter movement was mounted in a Military Standard type MS 33549 case using a 2.75 inch dial to simulate the actual X-15 instrument.

DYNAMIC PRESSURE INDICATOR

A linear 270° micro-ammeter movement was fitted to an MS type case. A voltage directly from the dynamic flight parameter computer drove the meter movement.

ROLL ANGLE INDICATOR

Roll angle was the second experimentally displayed flight parameter and was indicated on a dual indicating micro-ammeter movement through two needles indicating on a common scale. To convert the instrument to a simple roll angle indicator, the command needle was biased out of the field of view, as with the angle of attack indicator.

INERTIAL HEIGHT INDICATOR

The inertial height indicator was a dual concentric synchro-receiver instrument driving two needles independently. Two synchro transmitters were driven by a "Transidyne" servo, one directly driving the 10,000 ft. needle and the other, through a 10:1 reduction, driving the 100,000 ft. needle. Due to the low rotational speeds of the synchro drive, a synchronizing network was found to be unnecessary. Command voltage came directly from the flight dynamics computer to drive the servo. Maximum range of the indicator and drive was 1,000,000 ft.

INERTIAL SPEED

A single turn servo drove the inertial height indicator through a 400 cps synchro transmitter-receiver set. The maximum range of the instrument was 7,000 ft/sec. with the drive signal coming directly from the flight dynamics computer.

INERTIAL CLIMB INDICATOR

The maximum range of positive and negative 1000 ft./sec. rate of climb was indicated on a calibrated zero center 90° micro-ammeter instrument. A non-linear thyrite shaping circuit served to expand the scale around zero rate of climb. To prevent meter overload at high rates of climb, diode limiting circuits were incorporated in the flight dynamics computer.

AJB-3 ALL ATTITUDE INDICATOR

A Lear Model 4060E type AJB-3 all attitude indicator with associated drive circuitry was used to display roll, pitch and yaw information. Auxiliary position servos driven from the flight dynamics computer provided the synchro signal necessary for operation of this instrument. A separate 3 Ø power supply and servo amplifier package were mounted remote from the indicator.

COCKPIT CONFIGURATION AND LIGHTING

A simulated single seat aircraft cockpit shell was modified to resemble the X-15 pilot compartment. Seating, control and instrument panel positions and dimensions were maintained from the X-15 vehicle. Instrument panel lighting in the blacked out canopy was achieved through two 28 volt floodlights located behind the subject-pilot at head level.

CONTROL CONSOLE

A central console was provided for control and monitoring. Switching for the selection of all experimentally variable conditions was accomplished from this console. Incorporated in the console were audio mixers and amplifiers for the various audio functions. The auxiliary verbal communications task signal and intercom signal were mixed and presented only through the left auditory channel. The auditory display signals were presented on both channels to provide a proper binaural auditory signal.

APPENDIX K

MECHANIZATION OF THE SIMULATION FOR THE DISPLAY EVALUATION PHASE

FLIGHT DYNAMICS

The primary requirement for the experimental apparatus was to provide the subjects with a "vehicle" which would provide a task which would be a reasonable representation of the tasks required in flying the X-15. Essential characteristics implied by this statement include (1) the minimization of any negative transfer from the actual aircraft (or its high fidelity simulation with which most subjects had been exposed) and (2) that the tasks and workload required in the simulator were similar to actual flight.

An "altitude mission" was selected for the simulation. The flight profile is represented by Figure K1. Normal procedure currently used in actual flight dictates that the profile be flown by establishing, maintaining or changing critical parameters (such as angle of attack) in conjunction with an elapsed time clock (see Figure M1). Provision for using a command indicator (either visual or auditory) was a necessary addition for the mechanization.

Major features of the simulation include:

1. Simulation of the rigid body dynamics of the X-15.
2. Simulation of the control systems.
3. Simulation of the augmented damping system (SAS).
4. A circuit for the simulation of turbulence.
5. Circuits to augment the angle of attack and roll outputs to the auditory displays.
6. Outputs to drive the displays.

No provision was made for landing. This simplified the mechanization since no huge changes in heading nor low altitude (below 48, 000 feet) capability were required. Moreover, no outside visual display was required.

The procedure for developing the dynamic simulation was:

1. Aerodynamics data were investigated and a set of simplified equations based on small angle approximations were mechanized.

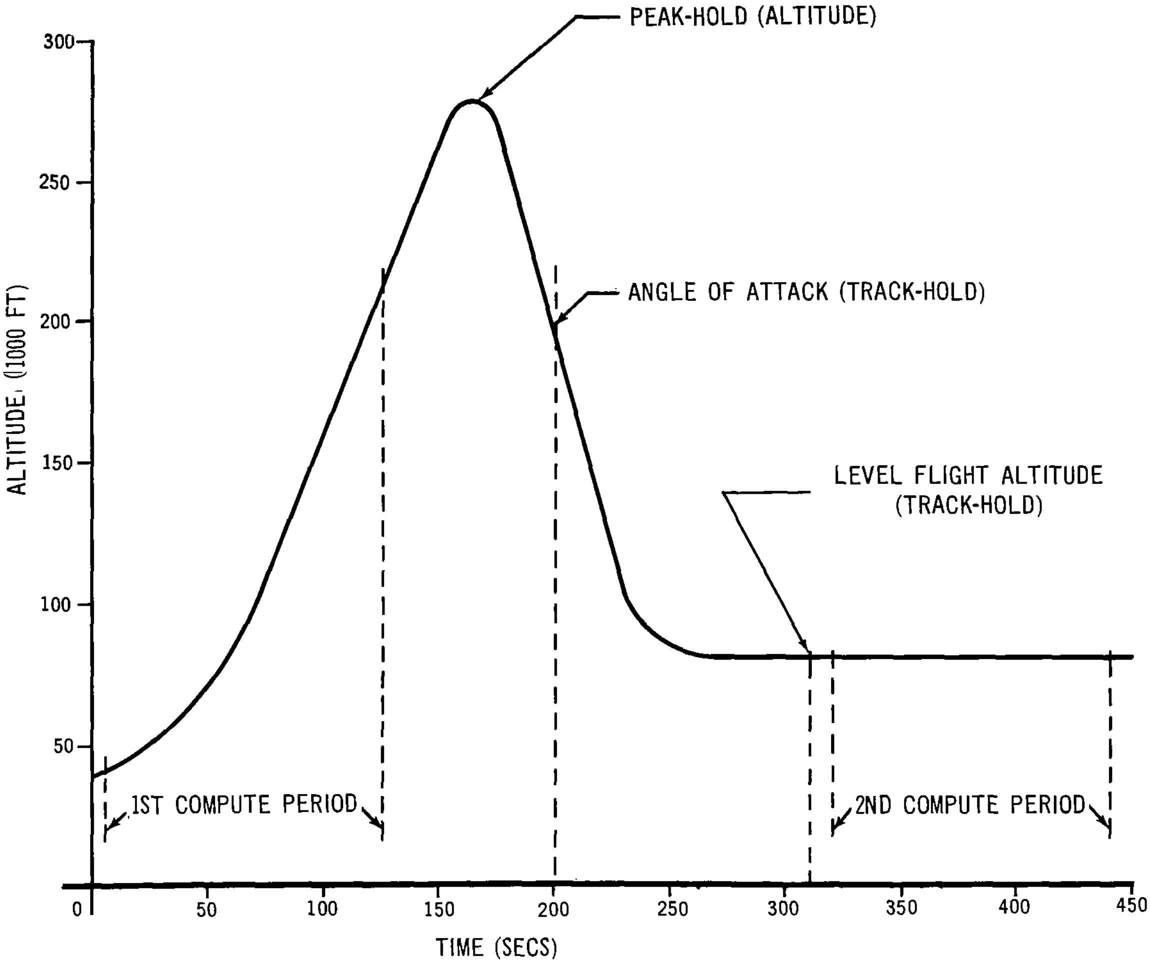


Figure Kl: Altitude Mission Profile

2. The thrust and weight factors were adjusted to fit the specific profile.

3. The short period dynamics were adjusted by using slip inputs at various points along the profile.

4. The resulting dynamics were "flown" by several people who were familiar with the NASA simulator located at Edwards Air Force Base. Modifications resulted from their comments.

The resulting dynamic equations are indicated in Table K1. The analog circuits are presented in Figures K2 through K5. Figure K6 is a schematic diagram of the entire simulation.

Characteristics of the resultant simulation were compared with those of the X-15. The profiles flown by a check pilot were very similar to an actual altitude mission profile as indicated in relevant reports. There were, however some exceptions:

1. The load factor was too high during initial rotation.

2. The elevator could not be trimmed for re-entry until later in the profile than normal. This was due to the incorporation of reaction and aerodynamic controls in one controller.

Step inputs to the control surfaces at various points along the profile indicated the simulation was close to critically damped throughout the profile with dampers on. With the dampers off, the simulation varied in frequency and damping ratio. This variation, while not identical to that of the X-15, was at least representative of the change in handling qualities.

The dynamic pressure function was generated by using an exponential approximation to the density variation with altitude. In forming the analog mechanization a fixed logarithm in function was used. (This circuit and other circuits below are indicated in Figure K4).

Turbulence was simulated by means of a random noise generator which formed a square wave normally oscillating about zero.

DATA COLLECTION

Datum error was accumulated during two periods within the flight profile and consisted of deviations in roll, angle of attack, and altitude. Three other parameters of interest were re-entry angle of attack, peak altitude, and level flight altitude.

TABLE K1: SIMPLIFIED FLIGHT EQUATIONS FOR X-15 SIMULATION

$$\dot{V} = T' - .56\Theta + q_0\,[-.02 - .0019\alpha]$$

$$\dot{\alpha} = \frac{1}{V}\,[1840 - q_0\alpha] + \dot{\Theta}$$

$$\dot{\beta} = \frac{1}{V}\,[32\Phi - 3.2q_0\beta] - \dot{\Psi}$$

$$\ddot{\Phi} = q_0\,[.04\delta_V - .008\beta + .04\delta' - 9.45\,\frac{\dot{\Phi}}{V} + .10^{-3}\dot{\Phi}] - 2.5\dot{\Phi} + 2.5\delta'$$

$$\ddot{\Theta} = q_0\,[-.027\alpha - .02\delta_H - 1.65\frac{\dot{\Theta}}{V} + .2\times10^{-3}\dot{\Theta}] - 4\dot{\Theta} - .3\delta_H$$

$$\ddot{\Psi} = q_0\,[.64\beta - .2\delta_V + .08\delta' - 6\frac{\dot{\Psi}}{V}] - 2.5\dot{\Psi} - 5\delta_V$$

$$\dot{h} = V\,[.0175\Theta - .0175\alpha]$$

$$N_Z = .543 \times 10^{-3} q_0\,\alpha$$

$$q_0 = 1.48\times10^{-3}\,10^{-1.88\times10^{-5}h}\,V^2$$

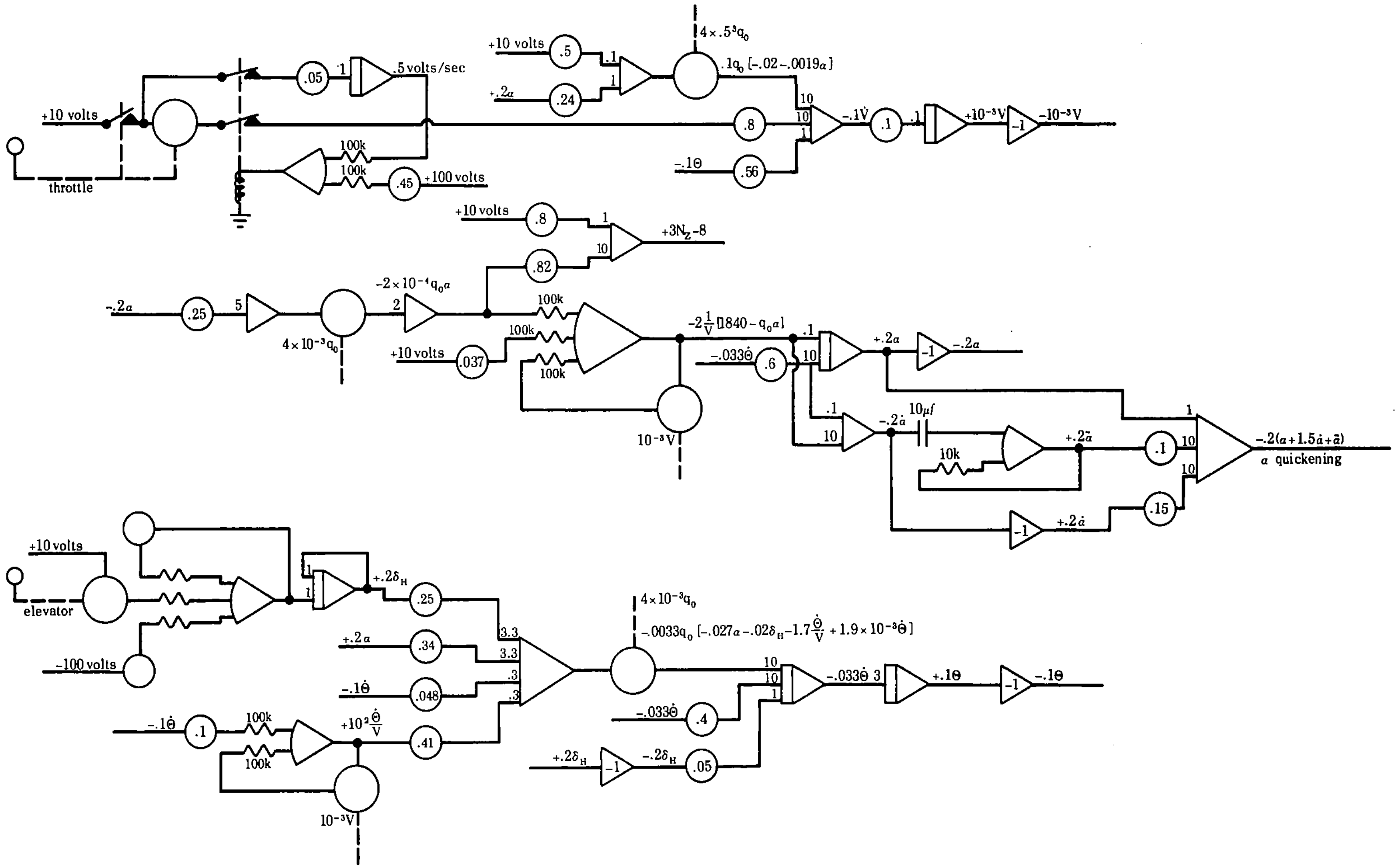


Figure K2: Analog Mechanization of the Longitudinal Dynamics for the X-15 Simulation

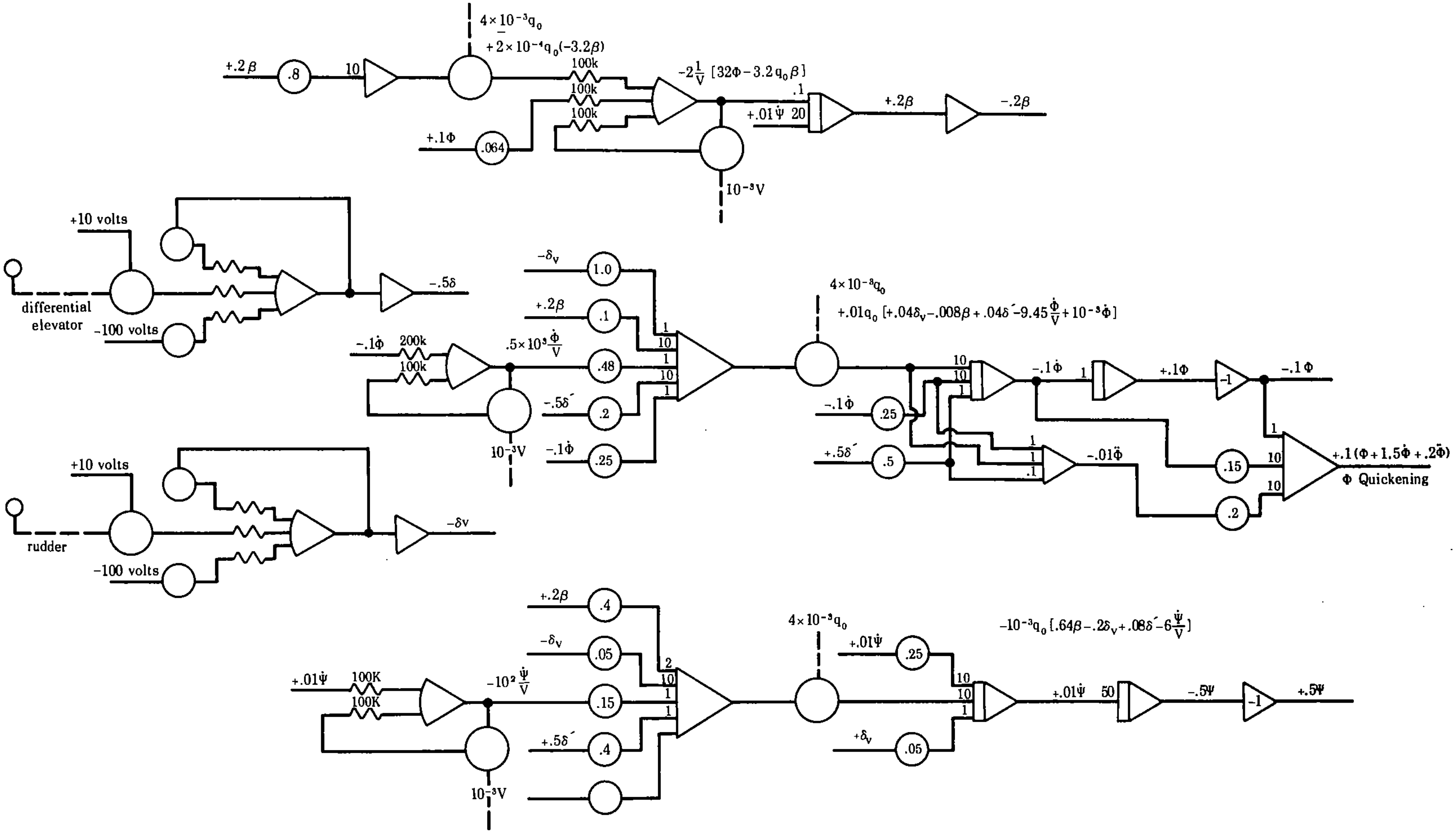


Figure K3: Analog Mechanization of the Lateral-Directional Dynamics for the X-15 Simulation

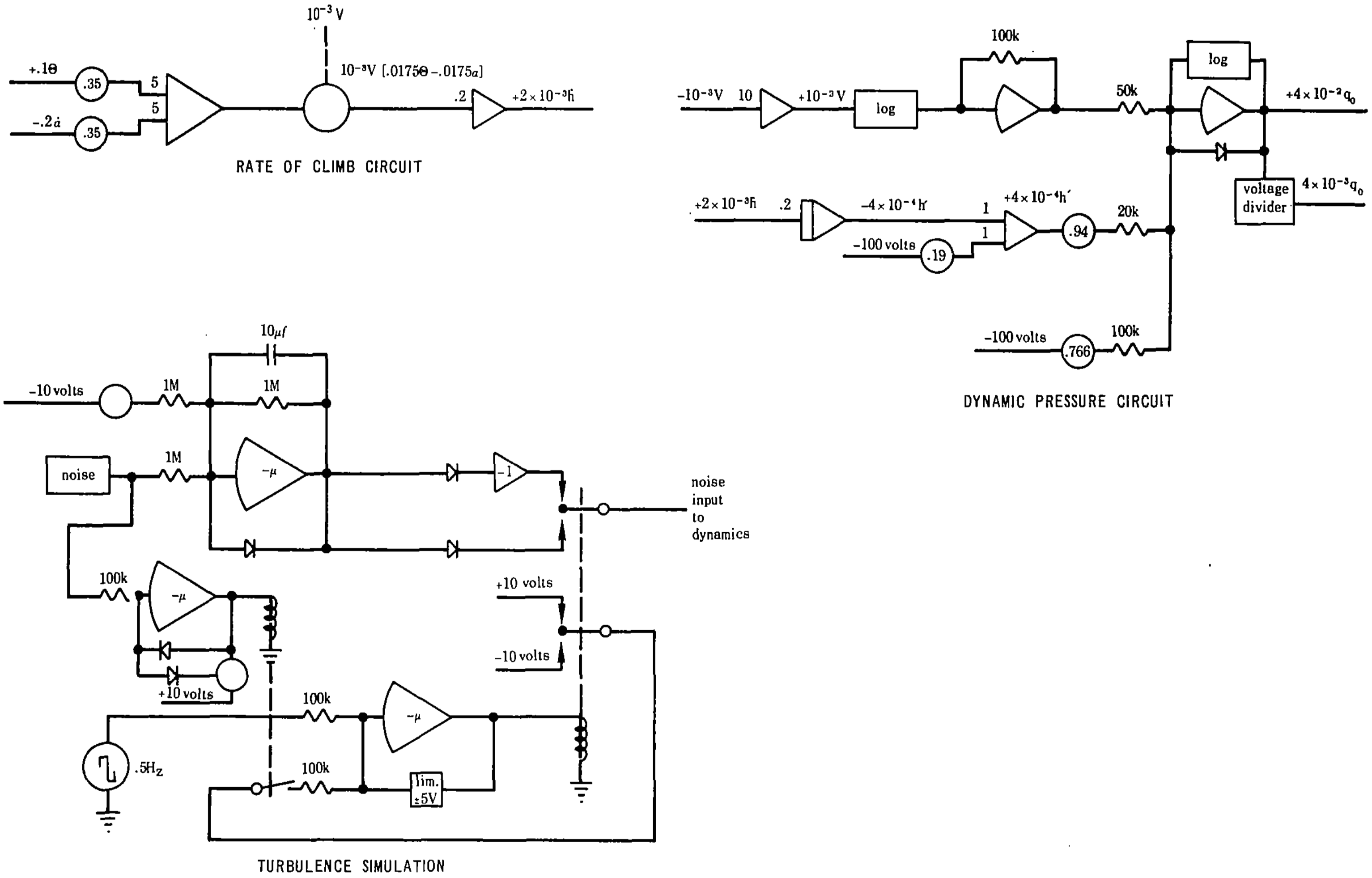


Figure K4: Additional Analog Circuits for the X-15 Simulator

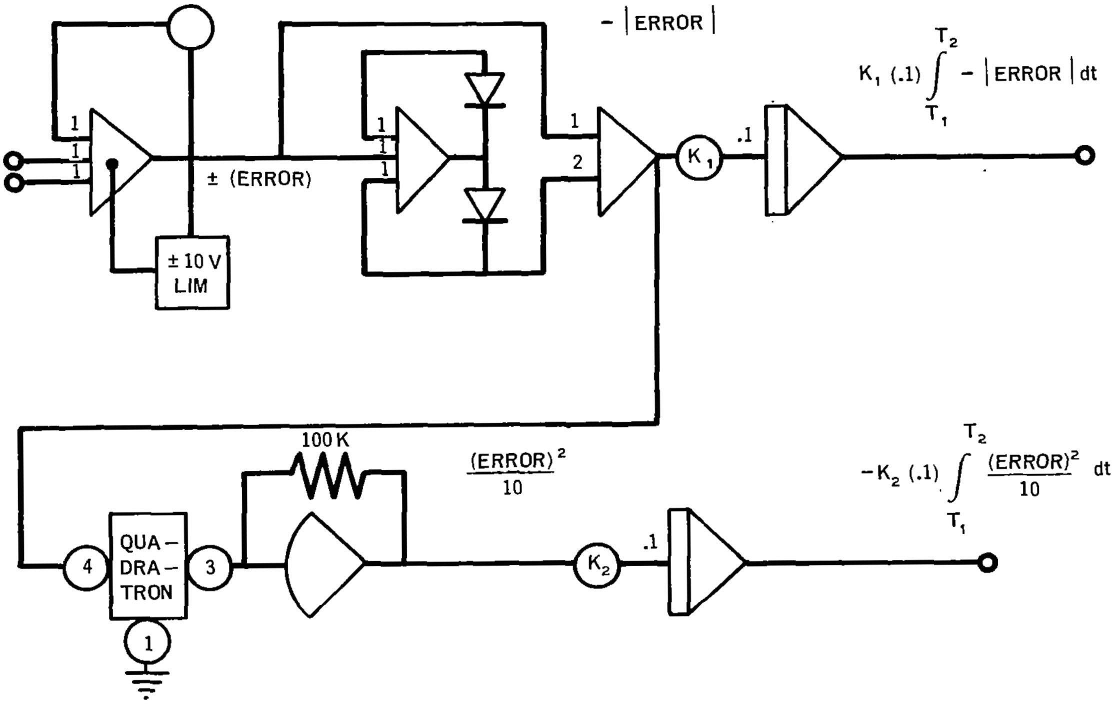


Figure K5: Typical Error Circuit

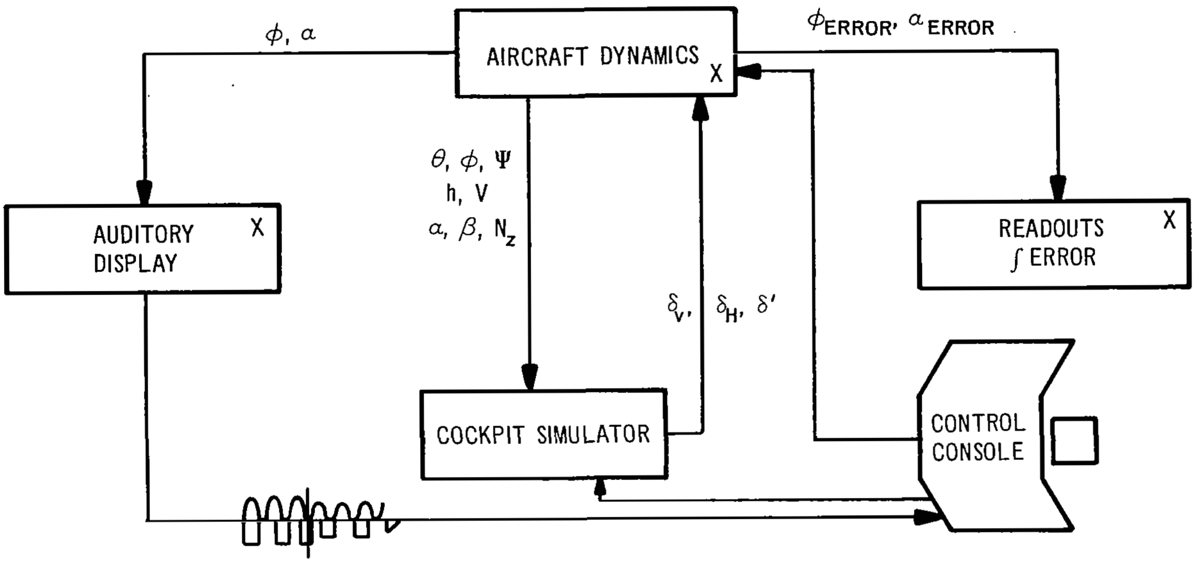


Figure K6: Schematic of the X-15 Simulator Used in the Display Evaluation Phase

Message No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
TIME (Seconds)	50	80	110	130	150	160	180	200	220	240	250	280	290	300	330	340	370	390	400	420
Message*	1	3	4	2	4	3	2	1	3	2	1	1	3	1	2	4	4	2	3	4
TIME (Seconds)	30	50	70	80	110	130	150	160	170	200	230	260	280	300	330	360	370	380	400	420
Message*	2	3	1	3	4	2	1	4	3	2	3	3	4	4	1	1	4	2	1	2
TIME (Seconds)	30	50	80	100	130	160	190	220	230	250	270	290	320	330	340	350	370	380	400	420
Message*	2	4	4	3	3	3	1	1	2	2	1	2	1	4	4	2	3	3	4	1
TIME (Seconds)	40	50	60	70	100	130	150	180	190	210	230	250	270	290	320	330	360	390	400	420
Message*	1	3	2	4	4	1	1	1	1	3	4	2	3	2	2	3	2	3	4	4
TIME (Seconds)	50	60	80	110	120	150	160	190	220	240	260	280	300	320	340	350	360	370	400	420
Message*	4	2	1	2	4	1	1	4	3	2	1	3	4	1	2	3	4	2	3	3
TIME (Seconds)	40	70	100	110	120	150	160	180	190	220	230	250	270	290	320	340	350	380	400	420
Message*	4	2	1	3	2	1	3	1	3	4	3	3	2	4	2	2	2	4	4	1
TIME (Seconds)	50	80	100	110	120	150	180	200	230	250	260	270	300	320	330	350	370	390	400	420
Message*	2	1	1	3	4	2	1	2	3	1	2	3	4	4	3	2	3	4	4	1
TIME (Seconds)	30	60	70	90	100	130	140	160	170	180	210	240	260	290	310	330	350	370	390	420
Message*	3	3	1	4	4	2	3	4	2	1	1	2	1	3	1	2	3	4	4	2

* Switch Position

APPENDIX M

REPRESENTATIVE INSTRUCTIONS TO SUBJECTS IN ACOUSTIC DISPLAY EVALUATION PHASE

Subjects were given a "General Introduction" prior to participation in this phase of the experiment. Prior to the 1st trial under each display condition, they were given a "Specific Introduction", including orientation and practice. Examples of these follow.

GENERAL INTRODUCTION

You are participating in an experiment concerned with the evaluation of acoustic displays in aerospace vehicles. For this purpose, we have developed a simulated aerospace vehicle, which is based upon the X-15, in which testing will occur.

The acoustic displays will encode command values of one or two flight parameters by audio cues. These will be described in detail to you later and you will be given some opportunity to become familiar with them. Some runs will not include acoustic displays. You will also be given a sheet of paper describing the mission profile to be "flown" during testing.

You will participate in alternate test runs to save time and reduce fatigue effects. Preceding your first run on the simulator you will have time to study the mission profile. Before the first run under a condition involving a display with which you are unfamiliar you will receive some practice with the display.

(Subjects are taken to simulator and allowed to examine it.)

Operational controls are the side stick, throttle, and rudder pedals. You may communicate with the experimenter by pressing the button located on the side stick and speaking into the microphone. The pitch trim knob operates as in the X-15.

SPECIFIC INTRODUCTION

(Acoustic Roll Angle Command Condition)

The mission profile you are to fly is described on this sheet of paper, (See Figure M1). Look it over and ask any questions you may have. You may keep this during runs.

(The flight timing watch, verbal communications task, and other details were explained to subjects)

Do you have any questions concerning vehicle controls or communication with the experimenter?

Roll angle is commanded acoustically as follows: an interrupted 500 c.p.s. tone is presented binaurally. Roll angle is commanded by differential loudness of the signal in both ears. The command is always to roll toward the loud side. Greater roll error is indicated by a greater discrepancy between the two loudness levels. You may now run through the first 30 seconds of the profile a few times to become familiar with the display. Note that "wings level" is commanded throughout this portion of the profile and hence you can get a feel for the sensitivity of the display by comparing with the visual display. Feel free to deliberately put in errors for this purpose. Just tell experimenter to "Drop" and he will start a run.

(3 such runs occurred)

Now you will fly a complete profile. Tell the experimenter to "Drop" when you are ready.

Time (Sec.)	Task Description
0	Drop; trim for rotation at $\alpha = 10^{\circ}$; start engine.
5	Hold $\alpha = 10^{\circ}$ and $\Phi = \beta = 0$.
39	Change α from 10° to 7°.
42	Hold $\alpha = 7^{\circ}$ and $\Phi = \beta = 0$.
90	Shut down engine; set trim to zero, change α from 7° to 0°.
170	Should be at peak altitude approximately 280, 000 feet; hold $\alpha = \beta = \Phi = 0$.
180	Start to set up re-entry angle of attack $\alpha = 20^{\circ}$.
200	Hold $\alpha = 20^{\circ}$.
240	Monitor load factor; keep $N_z < 5$ g's - also monitor inertial climb and reduce α such that $\dot{h}$ does not go through zero but stops right at zero; hold $\Phi = \beta = 0$.
300	For recovery set $\alpha = 5^{\circ}$ and hold $\alpha = 5^{\circ}$ and $\Phi = \beta = 0$.
450	End of run.

Figure M1: Flight Profile Instructions For Auditory Display Study (With No Angle of Attack Command)

Time (Sec.)	Task Description
0	Drop; trim for rotation at $\alpha = 10^{\circ}$; start engine
5	Track α command and hold $\Phi = \beta = O$.
90	Shut down engine; set trim to zero; track α command; hold $\Phi = \beta = O$.
170	Should be at peak altitude approximately 280, 000 feet; track α command, hold $\Phi = \beta = O$.
220	Have α command turned off as N_z approaches 5 g's. Monitor load factor holding $N_z < 5$ g's. Also monitor inertial climb and reduce α such at $\dot{h}$ does not go through zero but stops right at zero; hold $\Phi = \beta = O$.
300	Have α command turned on. Track α command and hold $\Phi = \beta = O$ for recovery.
450	End of run.

Figure M2: Flight Profile Instructions For Auditory Display Study (With Angle of Attack Command)

APPENDIX N

ORDER OF OCCURRENCE OF EXPERIMENTAL CONDITIONS IN ACOUSTIC DISPLAY EVALUATION PHASE

The order in which experimental conditions were presented to subjects during the acoustic display evaluation phase is shown in Figure N1. For each subject X display condition, the first 3 runs were practice, the second 3 runs were data collection runs with all dampers in and, finally, the last 2 runs were data collection runs with longitudinal dampers out during climb-out. General orientation and practice with displays preceded the 1st run under each condition.

	RUN NUMBER			
SUBJECT NUMBER	1, 5, 9, 13, 17, 21, 25, 29	2, 6, 10, 14 18, 22, 26, 30	3, 7, 11, 15 19, 23, 27, 31	4, 8, 12, 16 20, 24, 28, 32
1	A	B	C	D
2	B	D	A	C
3	C	A	D	B
4	D	C	B	A
5	W	X	Y	Z
6	X	Z	W	Y
7	Y	W	Z	X
8	Z	Y	X	W

A = CONVENTIONAL VISUAL DISPLAY
B = ROLL COMMAND VISUAL DISPLAY
C = ROLL COMMAND ACOUSTIC DISPLAY
D = AUGMENTED ROLL COMMAND ACOUSTIC DISPLAY

W = CONVENTIONAL VISUAL DISPLAY
X = ROLL AND ANGLE OF ATTACK COMMAND VISUAL DISPLAY
Y = ROLL AND ANGLE OF ATTACK COMMAND ACOUSTIC DISPLAY
Z = AUGMENTED ROLL AND ANGLE OF ATTACK COMMAND ACOUSTIC DISPLAY

Figure N1: Order of Occurrence of Experimental Conditions

APPENDIX O

SAMPLE OF QUESTIONNAIRE USED IN ACOUSTIC DISPLAY SELECTION PHASE

QUESTIONNAIRE - ACOUSTIC DISPLAY STUDY

NAME: ______________________________

DATE: ______________________________

Indicate your answers by placing an X on the scales provided. Add any comments which you have which relate to the questions or to the program in general.

1. Indicate the extent to which the total simulation requires performance comparable to that required in the operation of an aerospace vehicle such as the X-15. That is, to what extent do you feel that results of the study apply to the operational situation?

Not Comparable	Moderately Comparable	Very Comparable

Comments:

2. Do you believe that auditory displays, in general, have potential application in aerospace vehicles?

Definitely Not	Possibly, Worth Investigation	Definitely Yes

Comments:

3. Did the particular auditory code used in the study seem appropriate? That is, were the cues of suitable resolution, distinctness, etc? Were they compatible with the required responses?

No	Reasonably Appropriate	Yes

Comments:

4. Was the choice of parameter(s) acoustically displayed an appropriate one? That is, were they a suitable choice for evaluation of the feasibility of acoustic displays in aerospace vehicles?

No		Reasonably Appropriate			Yes

Comments:

5. Did you find the acoustic displays annoying or distracting?

No		Slightly			Yes, Very

Comments:

6. Was there interference between acoustic signals and verbal messages?

Not at All		Some, but Acceptable			Definitely

Comments:

Please add any general or specific comments or suggestions concerning the program:

APPENDIX P

ADDITIONAL ANALYSES AND SUMMARIES OF DATA FROM THE ACOUSTIC DISPLAY EVALUATION PHASE

Analyses and summaries of data from the acoustic display evaluation phase of the program, supplementary to those presented in the text, are presented below. The format is the same as that employed in the text.

TABLE P1: VARIANCE OF ABSOLUTE ERROR IN ANGLE OF ATTACK DURING CLIMB-OUT (All Dampers In)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	.006	.000	--
Display	(D)	3	38.792	2.586	--
Trials	(T)	2	11.983	2.903	--
N x D		3	28.021	1.868	--
D x T		6	8.248	1.778	--
N x T		2	15.342	3.717	--
N x D x T		6	6.413	1.382	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	4.800	4.157	5.367	4.171	4.624
2	7.106	1.624	4.387	5.317	4.608
Total	5.953	2.890	4.877	4.744	4.666

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Squared Degrees)

TABLE P2: VARIANCE OF ABSOLUTE ERROR IN ROLL ANGLE DURING CLIMB-OUT (All Dampers In)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	179.823	1.411	--
Display	(D)	3	57.934	1.283	--
Trials	(T)	2	25.239	.517	--
N x D		3	16.932	.375	--
D x T		6	6.550	.201	--
N x T		2	53.849	1.103	--
N x D x T		6	36.672	1.127	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	1.748	5.106	1.255	2.706	2.704
2	3.847	7.525	6.406	3.985	5.441
Total	2.798	6.315	3.831	3.346	4.073

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES (In Arbitrary Units)

TABLE P3: VARIANCE OF ABSOLUTE ERROR IN ANGLE OF ATTACK DURING "LEVEL" FLIGHT (All Dampers In)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	17.170	.965	--
Display	(D)	3	11.456	1.947	--
Trials	(T)	2	8.636	1.346	--
N x D		3	3.134	.533	--
D x T		6	11.983	1.577	--
N x T		2	1.030	.160	--
N x D x T		6	1.513	.199	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	1.701	1.479	3.376	1.216	1.943
2	.867	.521	1.701	1.301	1.097
Total	1.284	1.000	2.539	1.259	1.520

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES (In Squared Degrees)

TABLE P4: VARIANCE OF ABSOLUTE ERROR IN ROLL ANGLE DURING "LEVEL" FLIGHT (All Dampers In)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	2,525.371	.211	--
Display	(D)	3	1,012.484	1.331	--
Trials	(T)	2	884.585	.819	--
N x D		3	55.730	.073	--
D x T		6	861.016	2.119	--
N x T		2	19.938	.018	--
N x D x T		6	481.795	1.186	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	42.329	24.281	29.199	35.749	32.889
2	49.023	38.414	39.079	46.073	43.147
Total	45.676	31.347	34.139	40.911	38.018

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES (In Arbitrary Units)

TABLE P5: ALTITUDE DURING "LEVEL" FLIGHT

(310 Seconds After Drop-off. All Dampers In.)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	4,800,512	.009	--
Display	(D)	3	2,061,653	.090	--
Trials	(T)	2	239,325,000	2.057	--
N x D		3	19,596,667	.858	--
D x T		6	29,036,667	1.949	--
N x T		2	7,073,792	.061	--
N x D x T		6	15,306,667	1.018	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	76,418	74,722	75,952	77,072	76,041
2	75,781	77,812	76,081	76,280	76,489
Total	76,100	76,267	76,017	76,676	76,265

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Feet)

TABLE P6: VARIANCE OF ABSOLUTE ERROR IN ANGLE OF ATTACK DURING CLIMB-OUT (Longitudinal Dampers Out During Climb-out)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	26.360	.427	--
Display	(D)	3	4.425	.636	--
Trials	(T)	1	5.294	1.165	--
N x D		3	3.305	.475	--
D x T		3	18.953	2.084	--
N x T		1	6.313	1.389	--
N x D x T		3	18.322	2.015	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	10.170	11.512	11.324	10.941	10.987
2	9.727	9.388	10.770	8.927	9.703
Total	9.949	10.450	11.047	9.934	10.345

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES (In Squared Degrees)

TABLE P7: VARIANCE OF ABSOLUTE ERROR IN ROLL ANGLE DURING CLIMB-OUT (Longitudinal Dampers Out During Climb-out)

Source of Variation	df	MS	F	p
Number of Exp. Parameters	1	1,527.941	.437	--
Display	3	45.483	.704	--
Trials	1	313.782	.692	--
N x D	3	128.526	1.989	--
D x T	3	305.704	2.183	--
N x T	1	599.434	1.322	--
N x D x T	3	145.889	1.042	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	24.085	14.497	17.561	15.719	17.966
2	6.875	9.182	6.383	10.333	8.193
Total	15.480	11.840	11.972	13.026	13.080

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES (In Arbitrary Units)

TABLE P8: VARIANCE OF ABSOLUTE ERROR IN ANGLE OF ATTACK DURING "LEVEL" FLIGHT (Longitudinal Dampers Out During Climb-out)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	189.601	5.376	--
Display	(D)	3	24.177	3.132	≈ .05
Trials	(T)	1	2.018	.072	--
N x D		3	18.493	2.396	--
D x T		3	30.806	2.474	--
N x T		1	.563	.020	--
N x D x T		3	5.851	.470	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	8.033	2.921	5.110	3.767	4.958
2	1.658	1.720	1.985	.698	1.515
Total	4.846	2.321	3.547	2.232	3.237

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES
(In Squared Degrees)

TABLE P9: VARIANCE OF ABSOLUTE ERROR IN ROLL ANGLE DURING "LEVEL" FLIGHT (Longitudinal Dampers Out During Climb-out)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	3,030.809	.351	--
Display	(D)	3	431.050	.528	--
Trials	(T)	1	544.445	.925	--
N x D		3	1,195.288	1.463	--
D x T		3	680.153	1.371	--
N x T		1	740.294	1.257	--
N x D x T		3	236.612	.477	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	64.642	33.650	58.093	45.786	50.543
2	35.157	41.946	32.717	37.299	36.780
Total	49.899	37.798	45.405	41.542	43.662

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES (In Arbitrary Units)

TABLE P10: ALTITUDE DURING "LEVEL" FLIGHT

(310 Seconds After Drop-off. Longitudinal Dampers Out During Climb-Out)

Source of Variation		df	MS	F	p
Number of Exp. Parameters	(N)	1	986, 200, 000	1.310	--
Display	(D)	3	328, 086, 667	1.393	--
Trials	(T)	1	118, 620,000	1.103	--
N x D		3	356, 890, 000	1.515	--
D x T		3	425, 080, 000	1.736	--
N x T		1	286, 580, 000	2.664	--
N x D x T		3	547, 453, 333	2.235	--

A. ANALYSIS OF VARIANCE SUMMARY TABLE

	Display				
Number of Experimentally Displayed Parameters	Conventional Visual	Command Visual	Command Acoustic	Augmented Command Acoustic	Total
1	96,450	77,605	83,222	76,377	83,414
2	75,576	77,065	74,465	75,145	75,563
Total	86,013	77,335	78,844	75,761	79,489

B. MEAN PERFORMANCE AS A FUNCTION OF DISPLAY VARIABLES

(In Feet)

NASA-Langley, 1966 CR-509