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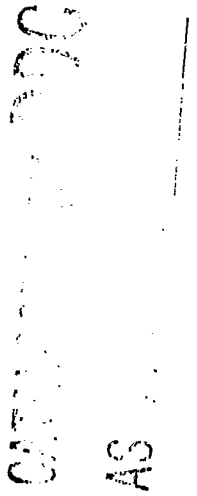
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AUDITORY LOCALIZATION OF A HELICOPTER --
FROM GROUND POSITION

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ABSTRACT

Three studies of unaided auditory localization of a helicopter are summarized. In each, an UH-1B helicopter in flight was the sound source and was localized by subjects on the ground. Absolute mean angular errors of different groups and under different conditions ranged from 8° to 24° and more, with smaller errors found under quieter conditions and at greater target ranges. Error size was not significantly affected by: flight direction; altitude changes from low nap-of-the-earth (20-60 feet) to low contour (100-110 feet); interfering noises from 90-mm. gunfire; or wearing a combat helmet. There were significant differences associated with interfering noise from passing vehicles and with subjects' auditory acuity.

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AUDITORY LOCALIZATION OF A HELICOPTER -- FROM GROUND POSITION

This report summarizes three related studies of ground-to-air auditory localization. In each of these studies, the subjects on the ground used unaided hearing to make azimuth localizations; and in each study, the UH-1B helicopter in flight was the sound source. The principal dependent variable was accuracy of azimuth pointing. Two of these studies were conducted in the Jolon Valley at Hunter-Liggett Military Reservation (HLMR), Calif., with the support of Combat Development Experimentation Center (CDEC), 27 February to 15 March 1963. The third study was conducted at Aberdeen Proving Ground (APG), Md., 13 to 15 May 1963.

The first study was concerned with two questions:

- a. Is the helicopter localized more accurately on departure than on approach?
- b. Is the helicopter localized more accurately on homing, rather than by-passing, courses? Homing courses are defined as those which pass directly over the subject, while by-passing courses are those that do not.

The second study was concerned with one further question:

Is the helicopter localized more accurately at 100-110 feet altitude than at lower altitudes (20-60 feet)?

The third study was concerned with two additional questions:

- a. Does wearing a steel combat helmet reduce accuracy of auditory localization?
- b. What is the range of audibility of the UH-1B, i.e., at what range is it detected (and localized)?

Several incidental questions, not listed here, were also investigated in the course of these studies; these questions will be discussed later in the results section.



Fig. 1. UH-1B HELICOPTER FLYING NAP-OF-THE-EARTH OVER JOLON VALLEY,
HUNTER-LIGGETT MILITARY RESERVATION

STUDIES I AND II

METHOD AND PROCEDURE

Flight Plans and Terrain

The first and second studies, conducted at HLMR, used three flight plans, each of which included linear-homing (or near-homing) and linear by-passing sections. The UH-1B helicopter pilot was instructed to fly nap-of-the-earth during the first study. Nap-of-the-earth flight is illustrated in Figure 1. The altitude during these flights varied from 20 to 60 feet above the surface, the higher altitude being required to pass over the highest trees in this sparsely wooded area. During the second study the altitude was maintained between 100 and 110 feet above the surface. The terrain was a relatively flat mountain valley, situated between two mountain ranges which ran in a general northwest-southeast direction. The ground was lightly wooded with scrub oak, which was thickly hung with Spanish moss. The mountain range to the west was less than one mile distant, and the range to the east was about one and one-half miles away.

Twelve ground-to-air panel markers were laid at positions previously surveyed, to provide marks at fixed angles and distances (0.5 km., 0.75 km., 1.00 km., and 2.00 km.) from the observation position. See Figures 2, 3, and 4 for illustrations of positions and flight plans. The three flight plans provide the same azimuth-marking points, but different orders of occurrence and directions of flight.

Aircraft

The UH-1B is a Bell helicopter powered by a gas turbine, with a main rotor that has two 21-inch chord blades and a 44-foot rotor diameter; a tail rotor measuring 8 feet 6 inches from tip to tip; and a tail-pipe directed toward the rear. All of these, along with the engine and gears, contribute to its total noise output. The UH-1B noise spectrum has a negative slope, with several relative maxima and the absolute maximum below 100 cycles per second. The over-all sound-pressure level is not markedly different from front to rear or side to side (1). In the experiments described here, the helicopter was operated by a pilot and a co-pilot, with the co-pilot acting as signal-man, reporting by radio to the subject position precisely as the aircraft passed over the ground-to-air panel markers. The co-pilot reported, "Mark C" (or the letter designating the panel position), followed by the heading of the aircraft in degrees and its speed in knots.

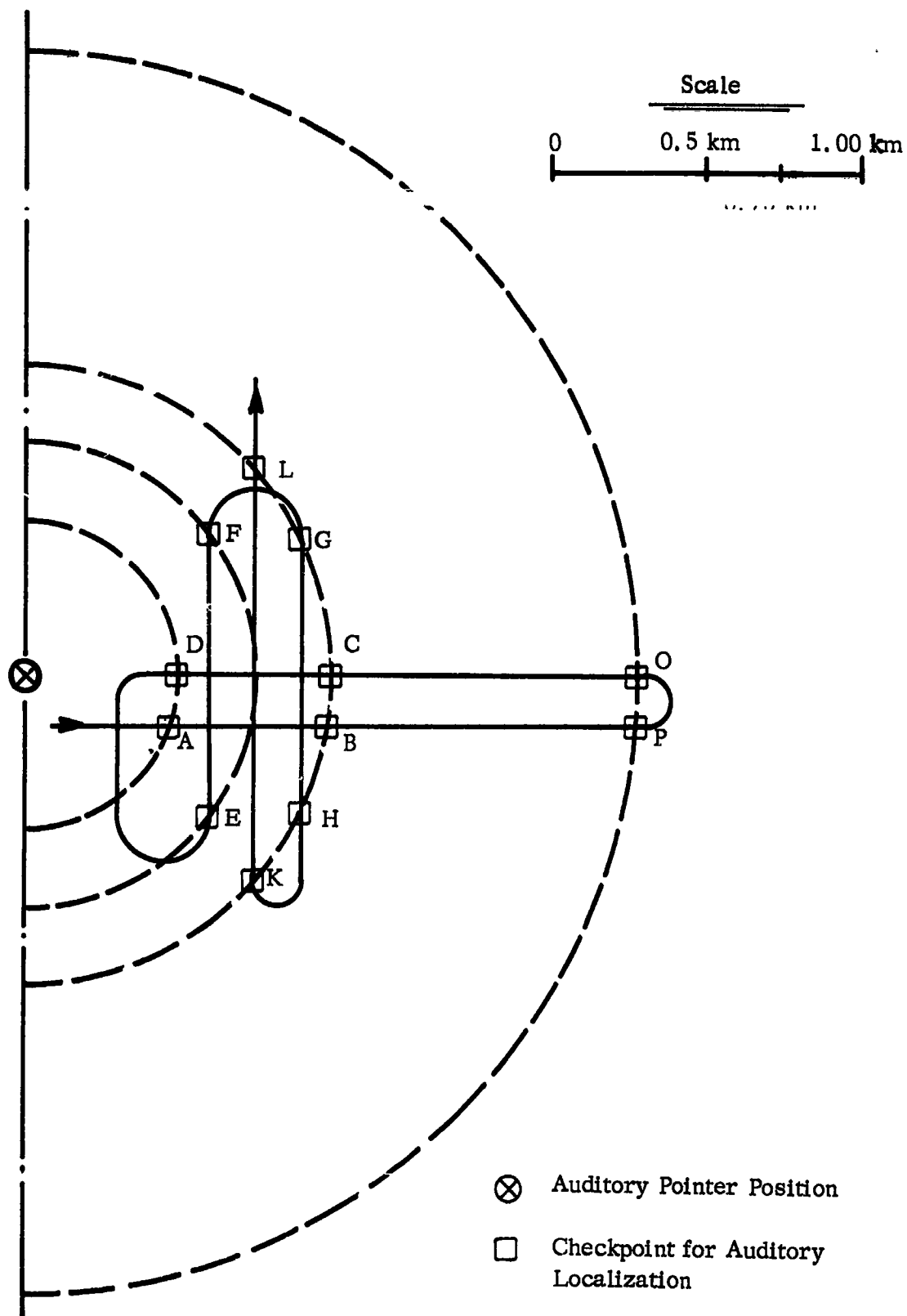


Fig. 2. FLIGHT PLAN 1

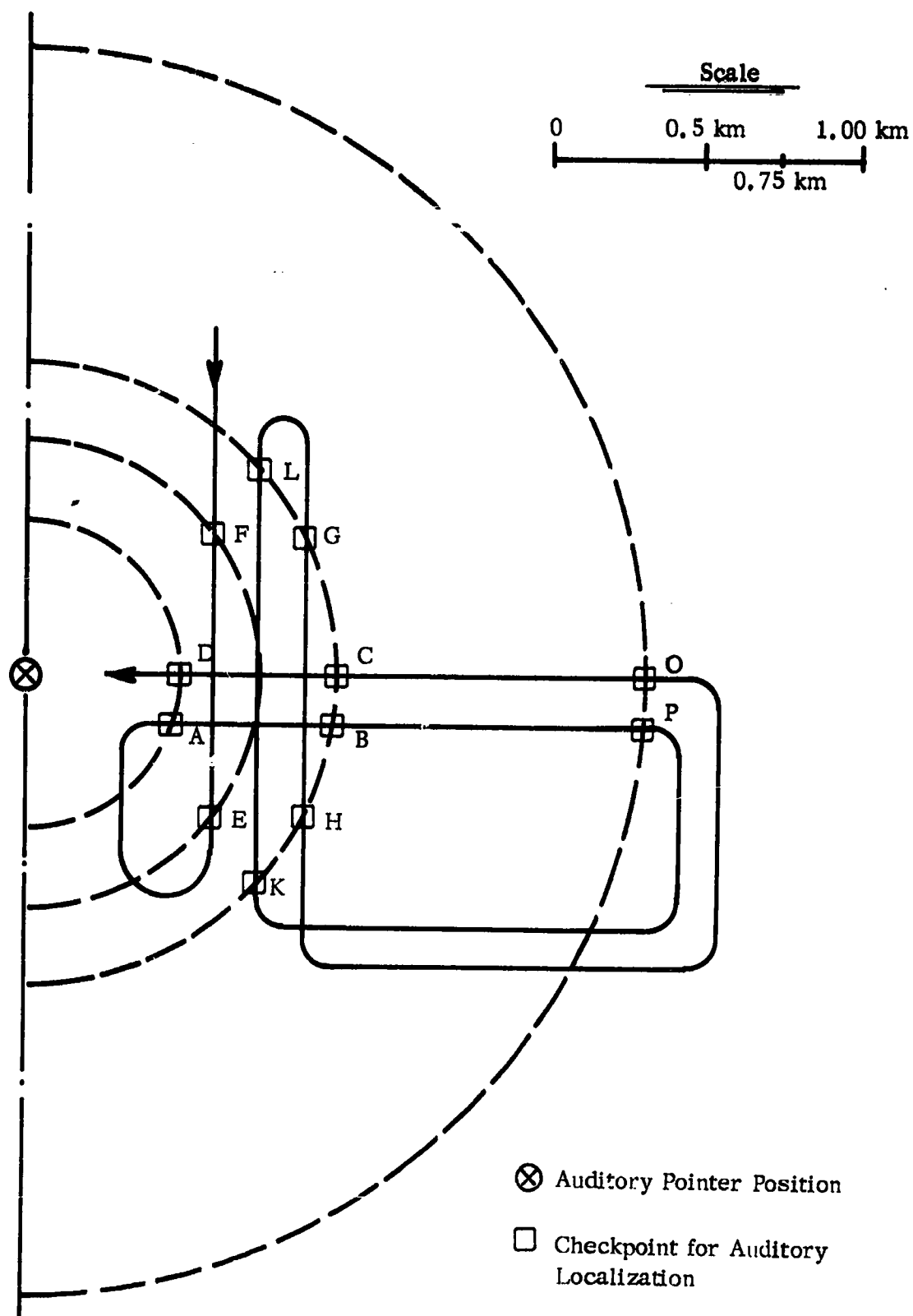


Fig. 3. FLIGHT PLAN 2

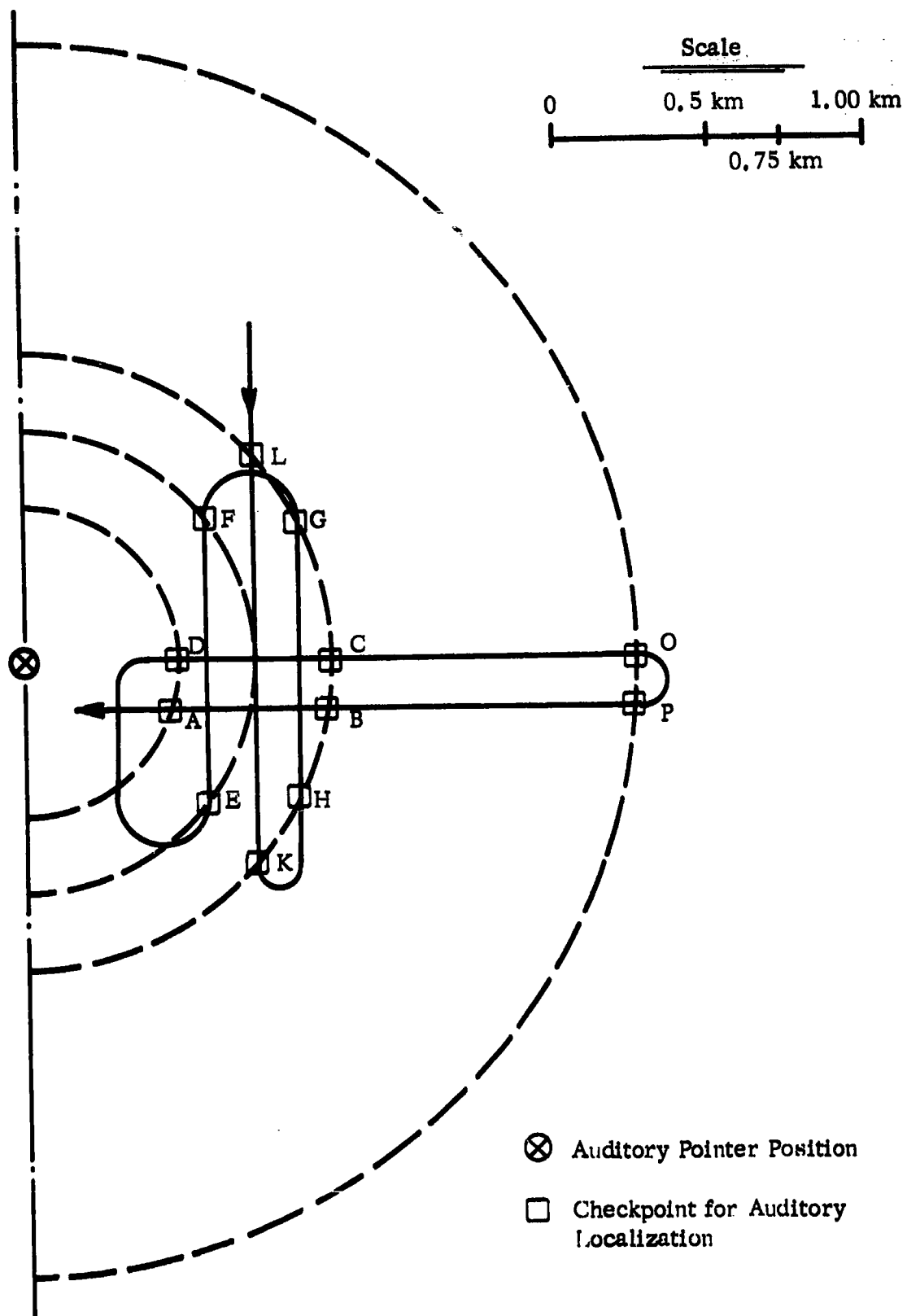


Fig. 4. FLIGHT PLAN 3

Subjects

The subjects were U. S. Army riflemen with normal hearing and visual acuity, as indicated by Profile 1 in their medical records. Twenty men served in Study I and 18 in Study II, but, because of instrumentation difficulties, Study I yielded only ten complete data records, and Study II yielded only 13 complete records for statistical analysis.

Equipment and Procedure

In order to record the subjects' judgment of target location, the Human Engineering Laboratories designed and constructed an azimuth table, which could be staked into position. The azimuth table pointer was free to rotate 360° above a clear plastic top. Photo data were recorded with a Bell and Howell Autoload 16-mm. movie camera, set for single-frame operation. The camera had a Wollensak 13-mm. f/1.2 T. V. Raptar Wide-Angle lens. This camera was mounted three feet below the clear plastic top so it could photograph the angular pointer position when a remote switch was operated. The pointer position was recorded on signal from the co-pilot as the aircraft passed over the ground-to-air panel markers. Each subject served on one run with one flight plan only. He was instructed to continue to point to the position of the aircraft during the entire run, whether or not the aircraft was audible. He was also required to report whenever the aircraft passed in or out of his hearing range. The subject position was so screened by vegetation that the aircraft was obscured from vision at all times except during turns near the subject position. Thus the subject had to rely on auditory localization exclusively. Each subject's record consisted of 12 sequential photographs, which could be converted into angular error scores.

RESULTS AND DISCUSSION

Mean Errors, Flight Direction, and Range

For all the 23 subjects and all 12 points average (absolute mean) angular error was 9° , with a 95 percent confidence interval ranging from 7° to 12° . Such results indicate that in 95 samples out of 100, the mean will be between 7° and 12° . Though this is a large mean error, it is small compared to the error of 20° found by Eyring in his study of jungle acoustics (2). It also proved to be smaller than the mean error found in a subsequent study in the noisier environment of Aberdeen Proving Ground. In comparisons of homing versus by-passing courses, and of approaching versus departing courses, there were no significant differences in angular accuracy.* There was a tendency for errors to be greater on approach than on departure (a mean of 10° versus a mean of 7°), but this difference was not statistically significant. Approaching and departing runs did differ significantly in the incidence of reports by subjects that they could not hear the aircraft. The great majority of such reports occurred on departing runs, and at the two points which were two kilometers distant. But mean errors at these points were no greater than at other points. Therefore, the report "cannot hear" at ranges of one or two kilometers was not related to a significant decrement in performance.

Range

Range, from 0.5 kilometers to 2.0 kilometers, was not significantly related to error size.** In these two studies the limited range kept the helicopter within normal hearing range but did not provide much variation for statistical comparisons. Therefore, it seemed advisable to consider the use of larger ranges, perhaps even some extending beyond normal hearing limits, in a later study.

* As shown by one U-test and one analysis of variance.

** Approach versus departure and ranges (three) were compared in a blocks-by-rows-by-columns ($13 \times 2 \times 3$) analysis of variance on the 13 subjects of Study I. Range was rechecked in a row-by-column (23×4) analysis of variance using data from all 23 subjects of Studies I and II.

Altitude

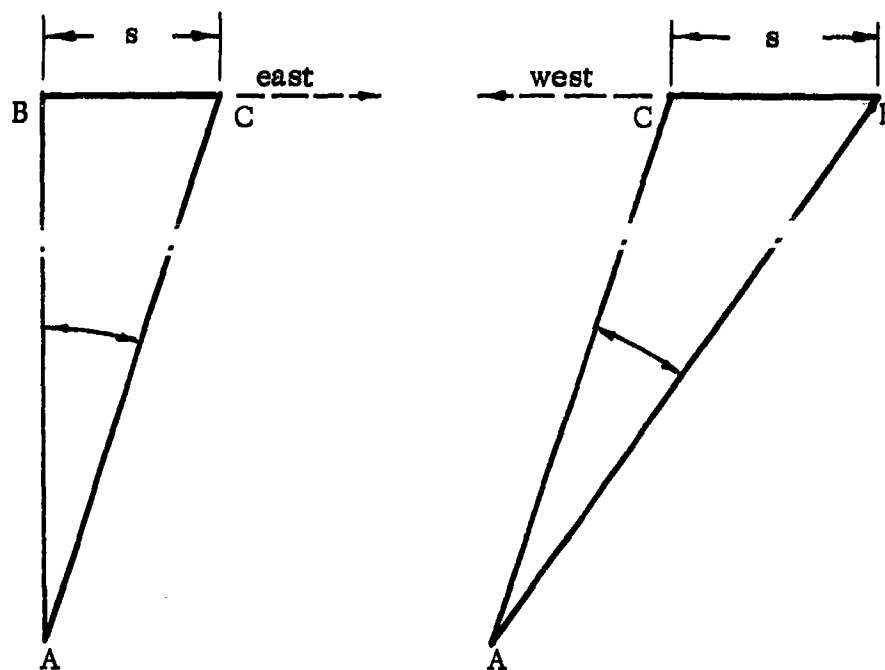
There was no significant difference in azimuth accuracy on extremely low-level contour flying (20 to 60 feet altitude) as compared with the higher-altitude (100 to 110 feet) contour flights. * While the results may be rather different with regard to visual detection, localization, and firing accuracy, this lack of difference between the minimum contour flying and the somewhat higher (and safer) level of 100 feet suggests that the higher level might be preferred tactically, if other considerations are equal.

Interfering Noise

During the collection of data for Study I, there was coincidental firing from 90-mm. guns at approximately four-fifths mile distance on five out of the 13 runs. On these five runs the firing was at a moderately rapid rate, involving several rounds per minute. Though this condition was not planned, it provided an opportunity to gather data related to combat conditions, so these instances were recorded and later subjected to statistical analysis, for comparison with the runs during which there was no such interference. Average errors were larger for these five subjects. The absolute mean error of the interfering-noise group was 12° , while the absolute mean error of the quiet group was 8° . However, this difference was not statistically significant, ** so it could reasonably be concluded that the noise from gunfire made no difference in accuracy of angular localization.

* t-test of significance of difference between means for low-level flight data versus higher-level flight data.

** t-test of significance of difference between means.



- A -- Subject position
- B -- Apparent position
- C -- Actual position, marking
point E, K, or H

Fig. 5. SCHEMES ILLUSTRATING PROBLEM OF APPARENT POSITION
VERSUS ACTUAL POSITION AT A MARKING POINT
SUCH AS E, K, OR H

Apparent Versus Actual Position

One intriguing question concerned the relatively slow velocity of sound over the distances involved in the by-passing courses only. When the helicopter is passing along a path which cuts over the mark at a radius of one kilometer, approximately three seconds are required for its sound to reach the subject. Yet, with transmission of control signals by radio plus the experimenter's reaction time in photographing the pointer position, the delay in recording is no more than one-half second. These facts suggest that the subject may be responding to sound emitted two or three seconds before the aircraft arrives over the mark, i. e., to its apparent position, rather than to its actual position. This apparent position can be determined mathematically from the helicopter's velocity and direction of flight, the known mark position, and the velocity of sound. Figure 5 illustrates the nature of the problem. The left illustration shows the general scheme for a problem involving a marking position such as E, K, or H (represented by C in Figure 5; see flight plans) as the helicopter flies eastward, by-passing the subject at A. The co-pilot gives the signal to mark the pointer position as he passes over the mark panel at C. However, the sound arriving at A as the photograph is taken is the sound emitted two to three seconds previously when the helicopter was over point B. While the helicopter travelled the distance s to the marking point, the sound travelled the distance BA to the subject. Similarly, the right illustration shows the general scheme for a problem involving the same marking position (E, K, or H) but with a westward direction of flight. The sound that reaches the subject at point A when the helicopter is passing over the mark at C, was actually emitted at B. The question then becomes: is the subject responding to the actual position (which would require him to anticipate the movement path of the stimulus), or is he responding to the apparent position (responding to the sound at the moment, and therefore trailing the helicopter in flight)? Apparent positions were calculated for the six mark positions and the two directions of flight, and for velocities of flight ranging from 45 to 80 knots. (See Appendix for method of solving this problem mathematically.) As indicated in Table 1, the differences between actual locations and apparent locations varied from two to six degrees at the different marks and velocities. When the question of what subjects were responding to -- actual position or apparent position -- was tested statistically, the distribution of errors favored the apparent position ($p < 0.0005$).^{*} This finding suggests that subjects were responding to the point from which the sound was emitted, rather than anticipating the direction of travel and velocity of the aircraft; thus their estimates trailed the aircraft somewhat more at higher velocities and greater distances.

^{*} Sign test for significance of difference.

TABLE 1

Apparent Positions Calculated for Two Different Flight Directions and Various Speeds
on By-Pass Course-Marking Points

		<u>Actual Locations</u>					
		H	K	E	G	L	F
		8°W	7°E	3°E	60°W	75°W	71°W
V _{ac/k*}	FLIGHT DIRECTION	<u>Apparent Locations</u>					
		H	K	E	G	L	F
45	E	12W	5E	0	63W	78W	74W
	W	5W	10E	6E	56W	73W	68W
50	E	12W	4E	1W	63W	79W	74W
	W	4W	11E	6E	56W	72W	67W
55	E	12W	4E	1W	63W	79W	75W
	W	4W	11E	7E	56W	72W	67W
60	E	13W	4E	1W	64W	79W	75W
	W	4W	11E	7E	55W	72W	67W
65	E	13W	3E	2W	65W	80W	75W
	W	3W	12E	7E	55W	71W	66W
70	E	14W	3E	2W	65W	80W	76W
	W	3W	12E	8E	54W	71W	66W
75	E	14W	3E	2W	66W	80W	76W
	W	2W	12E	8E	54W	71W	66W
80	E	14W	2E	3W	66W	81W	76W
	W	2W	13E	8E	54W	70W	65W

*V_{ac/k} = speed of aircraft in knots.

STUDY III

METHOD AND PROCEDURE

General Description

The previous studies had shown that angular accuracy is not significantly affected by these variables:

- a. homing versus by-passing courses;
- b. approaching versus departing courses;
- c. different ranges up to two kilometers; and
- d. extremely low-level (20-60-foot altitude) versus low-contour (100-110-foot altitude) flying.

In addition, there were no significant differences in azimuth accuracy on runs during which there was considerable interfering noise from 90-mm. firing at less than one-mile distance. Evidence about accuracy at greater ranges remained to be collected, along with data for other terrain and environmental conditions. The third study was planned to clarify the effect, if any, of the combat helmet on the soldier's azimuth accuracy in tracking the UH-1B helicopter. Also, greater ranges (up to six kilometers) were studied, to determine how range affects azimuth accuracy.

These questions about the effects of combat helmet and greater ranges were examined experimentally with an UH-1B helicopter and 18 subjects. The helicopter was required to follow a prescribed gently curving course, flying low-contour and/or nap-of-the-earth. The flight path passed over ground panel markers at ranges of 1, 2, 3, 4, and 6 kilometers from the observation point (Fig. 6). The helicopter made a "round trip" over the markers, turning and reversing direction after one pass over them. Subjects were required to wear the helmet for one pass (five observations) and remove the helmet for the return trip (vice versa on alternating subjects). Subjects tracked the vehicle continuously, and photographic readings of the pointer position were taken on signal from the crew chief (in the helicopter) as the aircraft passed over the markers at the fixed positions. Each subject thus provided ten photographic readings, including five different ranges and two different conditions (helmet versus no-helmet).

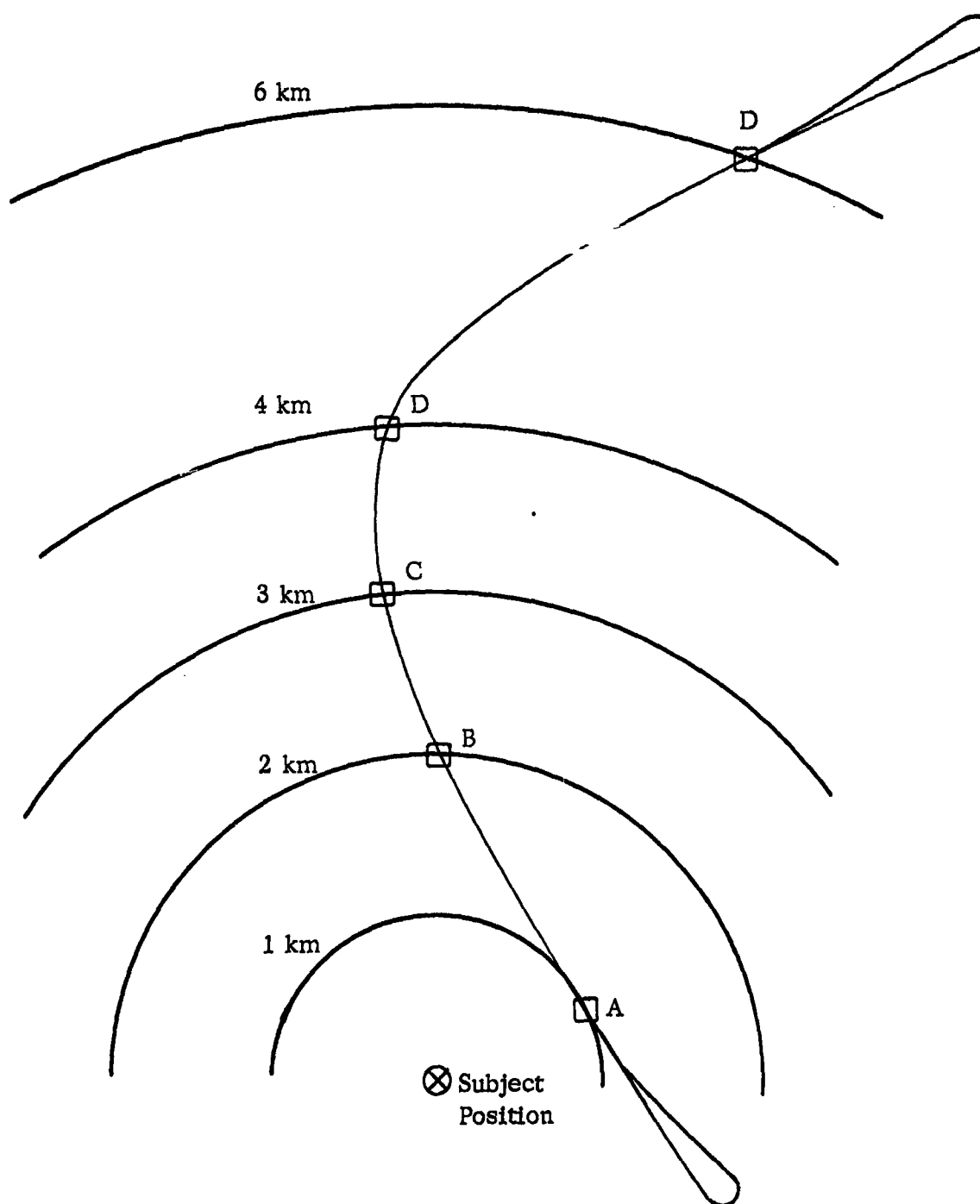


Fig. 6. LOCATION OF MARKING POINTS AND FLIGHT PLAN
FOR STUDY III, ABERDEEN PROVING GROUND, MD.

Terrain and Environment

The area used in this study was a crescent-shaped tract lying over the three-mile straightaway course and part of the cross-country course in the industrial area of Aberdeen Proving Ground, Md. The ground was gently rolling and moderately wooded. During the experiment, normal automotive tests were suspended, and there was very little traffic on the straightaway. However, there was intermittent traffic on the cross-country course, which passed very near the subject position, and there were electric and diesel trains on the railroad passing 1250 meters northwest of the subjects' position. This traffic on the railway and on the cross-country course proved to be sources of considerable interfering noise, which will be discussed below. The weather was humid on the mornings when tests were conducted, and some of the data were collected during light rain.

Aircraft

The UH-1B used was described in the CDEC studies report. A crew-chief replaced the co-pilot, and he was responsible for reporting precisely when the aircraft passed over the marker panels. He also reported heading in degrees, and speed in knots, at each point. Altitude varied generally between 60 and 80 feet, never rising above 100 feet. Speed was permitted to vary between 45 and 80 knots.

Subjects

The subjects were 18 men, 14 of whom came from a tank platoon, with four others from laboratory assignments. Because of the probability that some of these men had suffered hearing loss connected with their duties, all subjects were given audiometric examinations with the Rudmose audiometer. Twelve of the 14 tank crew members showed specific hearing loss in excess of 20 decibels, which was arbitrarily chosen as the criterion level. Two of the other subjects showed similar impairment, so that a total of 14 of the subjects showed hearing loss (within specific ranges) in one ear or the other. Of the 18 subjects used, two experienced such a high level of interfering noise during half of each of their runs that half of each set of data was discarded, and these two halves were arbitrarily pooled and treated as one subject, reducing the total to 17.

Equipment and Procedure

The photo data was collected with the same camera mounted on the azimuth table that was described in Studies I and II. Each subject served on one run only, yielding ten readings: five on approach and five on departure from the vicinity of the subject position. The subject position was sufficiently screened by terrain and vegetation that the helicopter was not visible from a few seconds past the one-kilometer point, and briefly during the turn-around on that end.

RESULTS AND DISCUSSION

Mean Errors, Flight Direction, and Range

The mean error for all readings and all points was 42° , a very large error in comparison with the 9° mean error found at HLMR, CDEC. This difference was attributed to the fact that the helicopter in this experiment proceeded out as far as six kilometers, though it was rarely audible even at four kilometers. Including the points over which the helicopter was reported as heard by the subject, but not the far points at which the aircraft was inaudible, the mean error was 18° . The rapid increase in error size between two- and three-kilometers range (Fig. 7) is paralleled by the sharp drop in number of subjects who report the helicopter audible at three and four kilometers (Fig. 8). Less than 50 percent of the subjects were able to hear the aircraft beyond three kilometers. Neither error size nor audible range was significantly different for approach versus departure.* When errors were calculated for each range separately, a distinct trend emerged, a perfect negative correlation between range and error size (Table 2). This decrease in error size as range increases contrasts with results from the previous CDEC studies, in which range effects were more limited, although it is consistent with the earlier work by Eyring (2), who reported such a negative relationship.

Helmet Effect

The steel combat helmet had no significant effect on the accuracy with which the subjects localized the noise source.**

* t-test on errors for approach versus departure.

** t-test on error for helmet condition versus no-helmet condition.

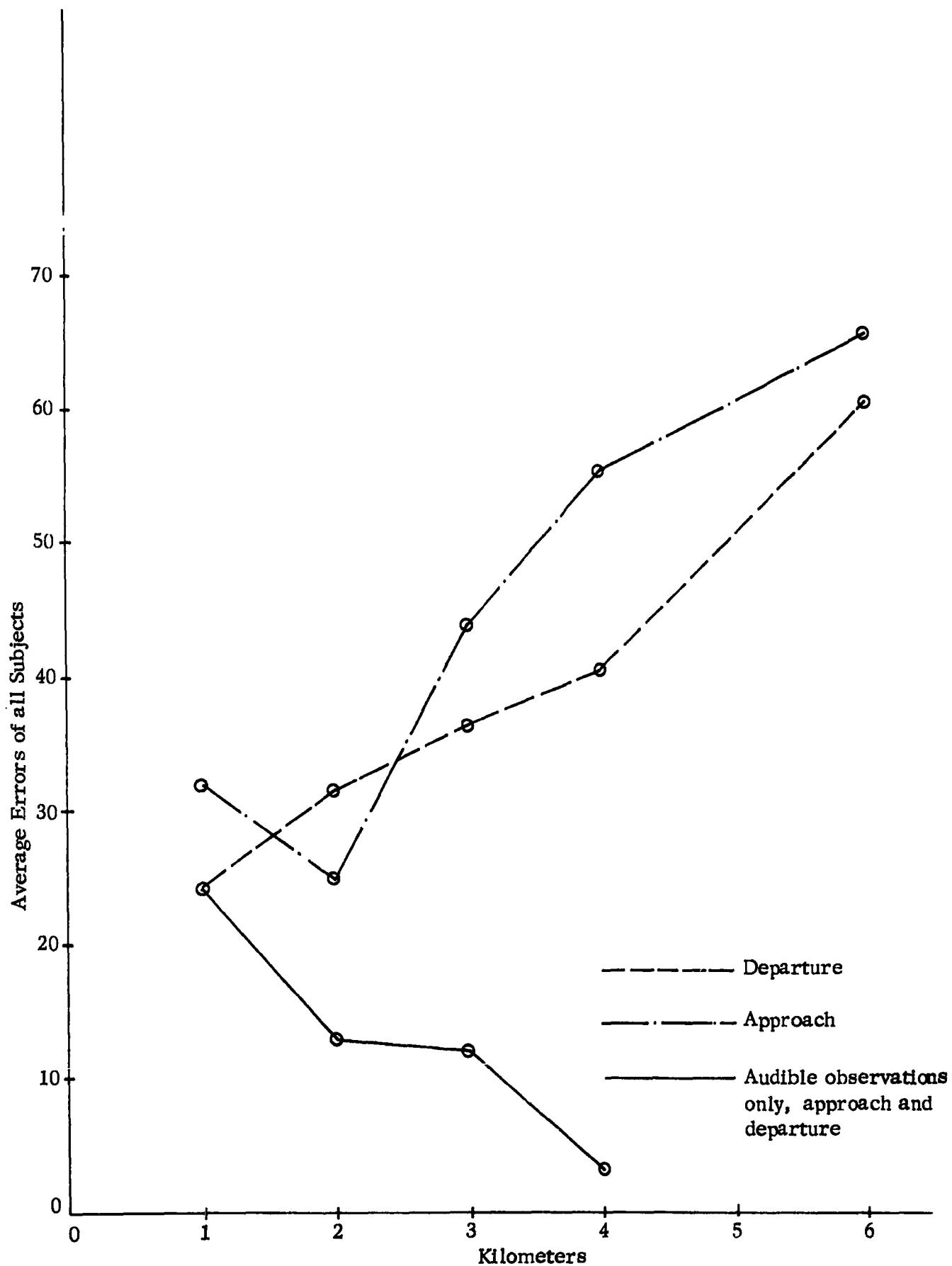


Fig. 7. MEAN ABSOLUTE ERRORS AT DIFFERENT RANGES

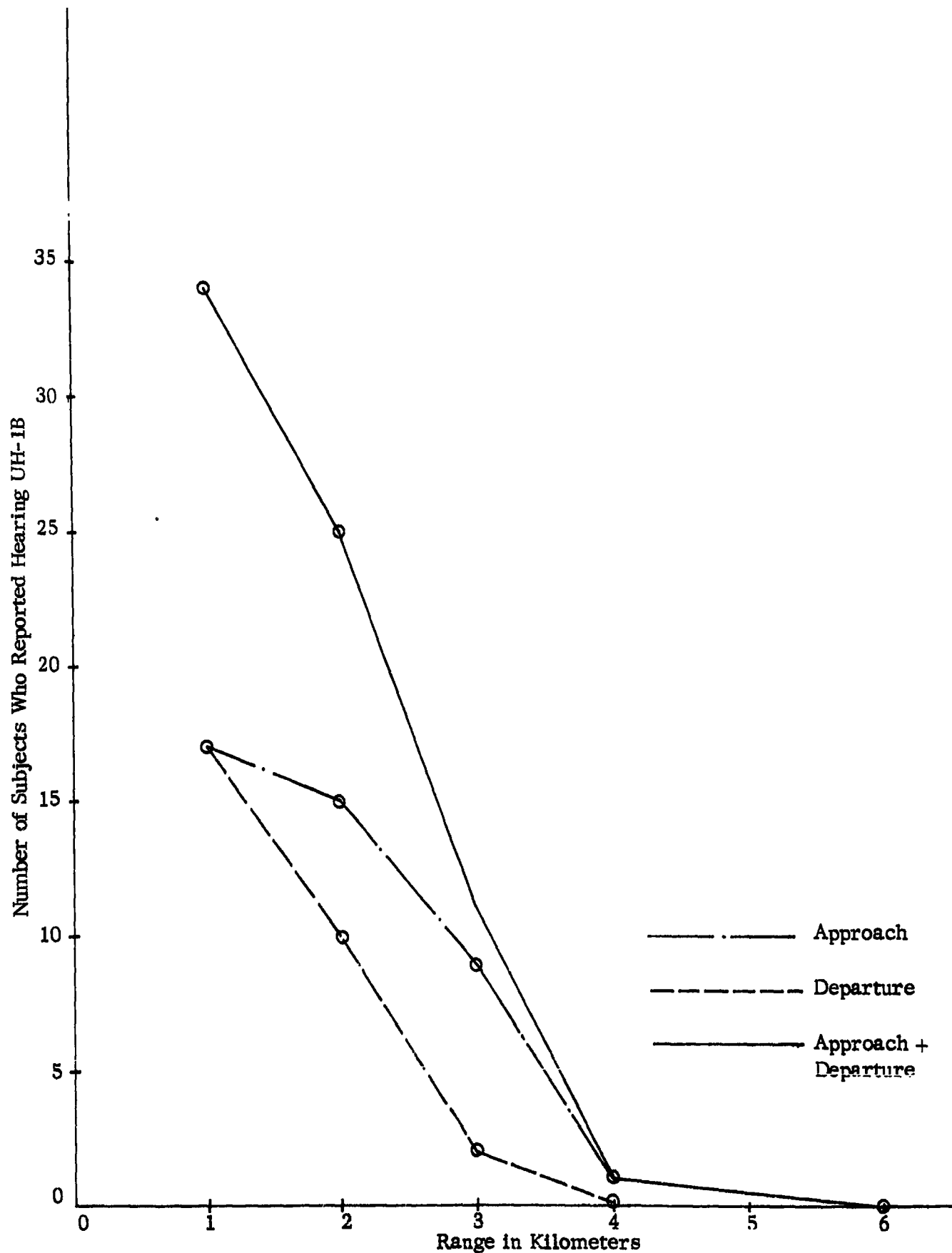


Fig. 8. NUMBER OF SUBJECTS REPORTING AIRCRAFT AUDIBLE AT DIFFERENT RANGES, DURING APPROACH AND DEPARTURE

TABLE 2

Mean Absolute Errors at Different Ranges

(Including only observations when aircraft was reported audible.)

Range in Kilometers	Mean Errors at Different Ranges	
	<u>N</u>	<u>Mean</u>
4	1	3°
3	11	12°
2	25	13°
1	34	24°

Interfering Noise

In the previous CDEC data, interfering noise from 90-mm. gunfire did not affect the accuracy of auditory localization. However, results from the Aberdeen Proving Ground (APG) data, with interference from other noisy vehicles, were markedly different. The proximity of the subjects' position to the APG cross-country vehicle test course made some traffic noises inevitable as weather improved. The passage of tanks, trucks, and armored personnel carriers was noted on the subject protocol in each case. Where such an interfering noise occurred, the reading was compared with another reading taken for the same subject at the same point. Thus the subject could serve as his own control in a one-tailed t-test of the prediction that the interference of engine and other vehicle noises would increase errors. The mean error with such masking noises was 18°. The mean error without such interfering noises was 6°. This difference was significant.* Considering these data in the light of the previous information, one may conclude that impulse noises, as of firing, are less disturbing to auditory localization of a vehicle than noise from other vehicles, which may produce continuous masking.

* t-test of significance of difference between correlated means, significant at 0.05 level.

Hearing Defects

There were four subjects with normal hearing and 14 subjects with hearing deficiencies, according to the criterion chosen. Since the subjects faced in a general northwest direction, left-side errors were scored westerly, and right-side errors were scored easterly. Table 3 shows that those subjects with deficiencies in the right ear, using predominantly left-side hearing, made a majority of errors in the westward direction; on the other hand, those subjects with deficiencies in the left ear, and thus better hearing on the right side, were equally apt to make east errors and west errors. This table excludes two subjects whose errors were evenly divided between east and west. These two subjects also had hearing loss in the left ear. The arrangement shown is not significantly different from chance expectation.*

TABLE 3

Sidedness of Hearing Damage Related to Direction of Error

Majority of Errors	Defect in Right Ear	Defect in Left Ear
West	5*	5*
East	1*	5*

* Each group had one subject with normal hearing.

The subjects with hearing deficiencies also showed a different magnitude of error performance. The mean error of this group was 20° . The four subjects with normal hearing showed a mean error of 10° . The difference between the normal and hearing-loss group was statistically significant.**

These data suggest that specific hearing deficiencies may not only affect the magnitude of errors, but their direction as well. However, it is difficult to explain why subjects with right-ear defect showed mainly left-side errors, while those with left-ear deficiencies showed no predominance of errors in either direction. Individual directional biases may be contaminated here with other possible sources of bias.

* Fisher's exact method yielded $p = 0.189$.

** t-test for significance of difference indicated $p < .01$ level.

GENERAL DISCUSSION

The range of absolute errors in these studies was greater than 90° . The range of means determined in each study was 180° . The large effects of certain variables which were manipulated. However, the largest part of this variation could be attributed to the aircraft passing out of audible range of the subject, ordinarily beyond two or three kilometers in distance. The greatest errors were thus made when the aircraft was far from the subject and, therefore, inaudible. Within the audible range for individual subjects, the trend was reversed: angular errors were greater at closer ranges. Within the audible range, the mean of errors was 90° in the first two studies and 180° in the third study. This difference of 90° between the HLMR data and the APG data could be attributed to two significant factors found in the APG study, and perhaps not entirely excluded in the HLMR studies. These two factors were: (1) masking from close passage of other vehicles, such as armored personnel carriers, tanks, and trucks; and (2) subjects' hearing defects.

These data suggest that specific hearing deficiencies may not only affect the magnitude, but also the direction, of errors. However, the data on direction are insufficient to allow a firm conclusion. There is no ready explanation for the fact that subjects with right-ear defect made mostly left-side errors, whereas subjects with left-ear defect made errors in both directions. Individual directional biases may be reflected here, and they may be contaminated by other undetermined sources of bias or consistent error.

Such an undetermined source of bias was indicated by the finding that, in all three studies, there was a general tendency for more errors to be in a westward direction than in an eastward direction. This finding could not be accounted for by prevailing winds, as they were nonexistent during most of the runs in which this bias was significant. This westward bias was more pronounced in the HLMR data than in the APG data. *

These data have several implications for future research. In field studies such as these, some interference from extraneous noises is to be expected. However, insofar as these masking noises have not been well-controlled heretofore, some controlled introduction of masking noises, both impulse and continuous, may be advisable in future experiments.

* Separate binomial probabilities were calculated and found to be significant for nine of the 23 subjects and at nine of the 12 marks in the HLMR data ($p < 0.01$ or < 0.001). In the APG data, the same trend emerged, but it was found to be statistically non-significant when only points within audible range were considered.

The high proportion of subjects with hearing loss, as indicated by audiometric examinations in the third study, pointed up the general need for such examinations in connection with auditory studies. The use of military subjects, and the possibility of significant differences in hearing-defect cases make such examinations mandatory.

Another suggestion refers to pointing behavior -- which is the main dependent variable in these studies. We do not know how accurately a group of military subjects can point to a target or signal. This pointing is rather different behavior from that required in aiming and firing a weapon. Pointing behavior may be relatively inaccurate even if the signal is visible. Future studies may be undertaken to determine subjects' ability to point toward auditory and/or visual signals. Such measurements, taken in advance of data collection in an auditory localization study, should yield information on individual consistency or bias.

SUMMARY

This report gives the results of three studies of accuracy of auditory localizations. In each study the sound source was an UH-1B helicopter in low-level flight and the subjects on the ground used unaided hearing to localize the aircraft noise. Their azimuth pointing was recorded photographically as the aircraft passed over previously fixed markers.

Mean absolute angular error was 9° in the first two studies combined, and 18° for observations while the aircraft was audible in the third study. Less than 50 percent of the subjects reported hearing the aircraft beyond 3 kilometers (km.), and no subject reported hearing the aircraft beyond 4 km. Errors became very large beyond 3 km.; but, within audible range, angular errors were smaller at greater ranges.

Absolute error size was not significantly affected by:

- a. nap-of-the-earth (20-60-feet-altitude) versus low-contour (100-110-feet-altitude) flying;
- b. approaching versus departing courses;
- c. homing versus by-passing courses;
- d. interfering noise from 90-mm. gunfire;
- e. wearing combat helmets.

While gunfire did not mask the helicopter noise, that is, the helicopter noise was continuously audible and could be localized during gunfire, the passage of other vehicles, such as trucks and tanks, did mask the helicopter noise and resulted in larger errors. Subjects who had specific hearing losses also showed significantly larger errors than subjects with normal hearing.

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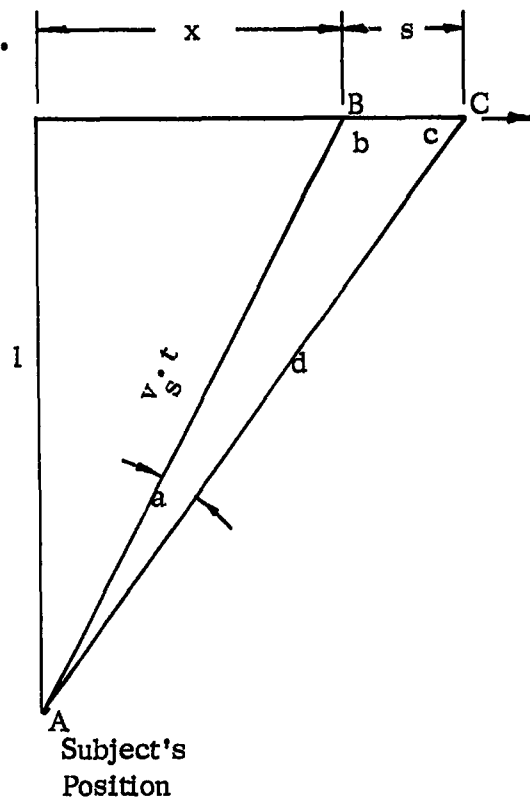
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APPENDIX

Method of Calculation of Apparent Position, Given Speed, Direction, and Actual Position

- a. The case in which an aircraft is flying east over a marking point, such as K, E, or H (denoted below as C).

Given: l , x , $v_{a/c}$, v_s , angle c , d .
The aircraft travels from B to C, a distance $s = v_{a/c} \cdot t$, while the sound travels a distance, $v_s \cdot t$, to the subject.



By the law of cosines: $(v_s \cdot t)^2 = (v_{a/c} \cdot t)^2 + d^2 - 2 \cdot v_{a/c} \cdot t \cdot d \cdot \cos. c$

Solving for t : $(v_s^2 - v_{a/c}^2) t^2 + 2 v_{a/c} \cdot d (\cos. c) t - d^2 = 0$

By the quadratic-equation formula:

$$t = \frac{-2 v_{a/c} \cdot d (\cos. c) \pm \sqrt{(2 v_{a/c} \cdot d \cos. c)^2 - (4) (v_s^2 - v_{a/c}^2) (-d^2)}}{2(v_s^2 - v_{a/c}^2)}$$

Then: $s = v_a \cdot t$

and solving for a
by the law of sines:

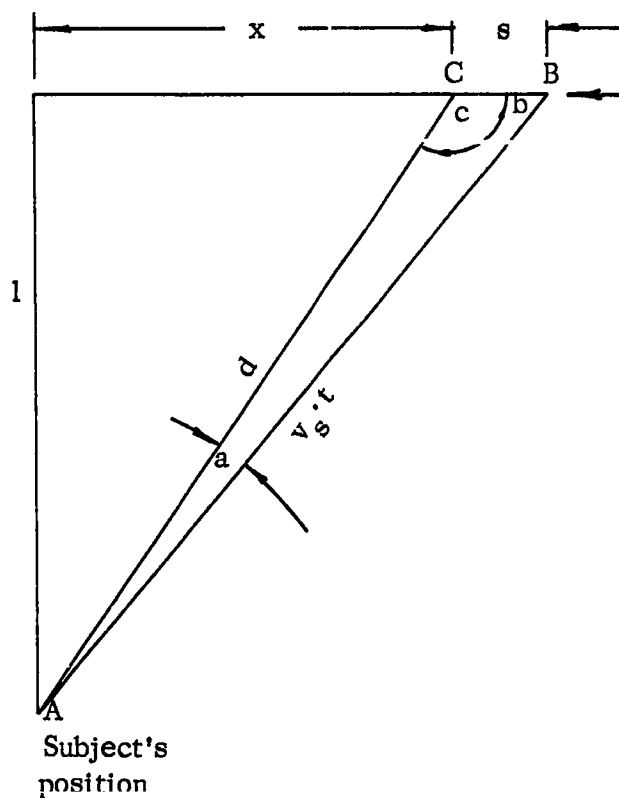
$$\sin a = \frac{s}{c} \sin c$$

$$a = \arcsin a$$

- b. The case in which an aircraft is flying west over the same point conforms to the scheme below, and has a very similar solution:

Given: same as above.

The aircraft travels from B to C, a distance, $s = v_a \cdot t$, while the sound travels a distance, $v_s \cdot t$, to the subject.



By the law of cosines: $(v_s \cdot t)^2 = (v_{a/c} \cdot t)^2 + d^2 - 2 \cdot v_{a/c} \cdot t \cdot d(\cos. c)$

Solving for t: $(v_s^2 - v_{a/c}^2) t^2 + 2 v_{a/c} \cdot d \cdot (\cos. c) \cdot t - d^2 = 0$

By the quadratic-equation formula:

$$t = \frac{-2 v_{a/c} \cdot d (\cos. c) \pm \sqrt{(2 v_{a/c} \cdot d \cdot \cos. c)^2 - 4(v_s^2 - v_{a/c}^2)(-d^2)}}{2(v_s^2 - v_{a/c}^2)}$$

Then: $s = v_{a/c} \cdot t$

and, solving for a
by the law of sines: $\sin a = \frac{s \sin c}{v_s \cdot t}$

$a = \arcsin a$

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