PM 87/34

Report No. DOT/FAA/PM-87/34

Project Report
ATC-152

Unalerted Air-to-Air Visual Acquisition

J.W. Andrews

26 November 1991

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

Prepared for the Federal Aviation Administration.

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
ATC-152	DOT/FAA/PM-87/34	

4. Title and Subtitle	5. Report Date
Unalerted Air-to-Air Visual Acquisition	26 November 1991
	6. Performing Organization Code
7. Author(s) J.W. Andrews	8. Performing Organization Report No. ATC-152
9. Performing Organization Name and Address Lincoln Laboratory, MIT P.O. Box 73 Lexington, MA 02173-9108	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFA-01-85-Z-02015
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, DC 20591	13. Type of Report and Period Covered Project Report 14. Sponsoring Agency Code

15. Supplementary Notes

This work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, under Air Force Contract F19628-90-C-0002.

16. Abstract

A series of flight tests were flown to measure pilot air-to-air visual acquisition performance for pilots employing unalerted visual search. Twenty-four general aviation subject pilots flew a cross-country route while an intercepting aircraft was controlled to produce three intercepts with altitude separation of 500 feet. Pilots received no traffic advisory information to alert them to the possible presence of the intercepting aircraft. Results were analyzed to estimate the instantaneous rate of visual acquisition for a visual target of specified size and contrast. The results were used to calibrate a mathematical model of visual acquisition that can be used to predict pilot performance under a range of conditions.

17. Key Words	18. Distribution Statement
mathematical model visual acquisition visual search	This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	43	

FORM DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Earlier studies have characterized the ability of pilots to visually acquire traffic when aided by the automatic traffic advisories of the Traffic Alert and Collision Avoidance System (TCAS). In that work, a mathematical model was developed that allowed prediction of visual search performance for a range of closing speeds and visual conditions. Unfortunately, many encounters occur in today's airspace for which no alerting traffic advisory is provided. The model can be applied to such cases merely by adjusting model parameters. However, parameter selection must be based upon flight test data. To obtain such data, a series of flight tests were flown to measure the air-to-air visual acquisition performance of pilots engaged in unalerted visual search.

Twenty-four general aviation pilots participated in the test. Subjects were carefully briefed so that visual search was perceived as only one aspect of the pilot techniques of interest to test personnel. Each subject, accompanied by a safety pilot, flew the Beech Bonanza aircraft on a 45 minute cross-country flight. During this flight, three airborne intercepts were scheduled using a Cessna 421 interceptor. The positions and closing rates of each aircraft was recorded by radar for later analysis. The time at which the subject saw the intercepting aircraft was recorded by the safety pilot.

Data analysis revealed that the instantaneous rate of visual acquisition for the subject pilots was

$$\frac{\beta A}{r^2}$$

where β is an empirically derived parameter found to be 17000 steradian/sec, A is the visual area of the target aircraft, and r is the target range. For example, for a target of 70 square feet at a range of 1 nmi, the instantaneous rate of visual acquisition is 3.2 percent per second. This rate is approximately eight times lower than the instantaneous acquisition rate for alerted search as determined from TCAS flight tests.

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1. INTRODUCTION

Flight tests were conducted to determine the ability of general aviation pilots, unalerted to the presence of traffic, to visually acquire other aircraft approaching on near collision courses. Previous flight tests at Lincoln Laboratory had provided data on visual acquisition performance when pilots are alerted by collision avoidance systems (see Ref. 1 and 2). A mathematical model of visual acquisition was developed to characterize the observed pilot performance. Although this model was applicable to both alerted and unalerted search, it could not be applied to unalerted search because of a lack of calibrating flight test data. In order to use the model to examine see-and-avoid reliability in today's airspace, it was necessary to conduct flight tests in which pilots received no alerting information to assist their search for traffic. This report describes the test procedures and test results for these flight tests.

2. THE VISUAL ACQUISITION MODEL

At any given instant, the likelihood of visual acquisition can be described in terms of the visual acquisition rate, λ, defined as follows:

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{P\ [\ acq\ in\ \Delta t\ ]}{\Delta t} \qquad (2\text{-}1)$$

The cumulative probability of visual acquisition is obtained by integrating the acquisition probabilities for each instant as the target aircraft approaches.

$$P\ [\ acq\ by\ t_2\ ] = 1.0 - \exp\ [\ - \int_{-\infty}^{t_2} \lambda(t)\ dt\ ] \qquad (2\text{-}2)$$

This equation describes a nonhomogeneous Poisson process. It is a general mathematical formulation that can be used to describe almost any type of visual search process. In order to make it useful, an expression for $\lambda(t)$ must be found. Experimental results (Ref. 1) have shown that for air-to-air visual search, λ is proportional to the product of the angular size of the visual target and its contrast with its background. When the exponential degradation of contrast with visual range is taken into account, the expression for λ then becomes

$$\lambda = \beta \frac{A}{r^2} \exp[-2.996 \frac{r}{R}] \qquad (2\text{-}3)$$

where A is the visual area presented by the target aircraft, r is the range of the target, and R is the visual range.

The cumulative probability of visual acquisition in a given situation can be obtained by inserting the expression for λ from equation (2-3) into equation (2-2). The resulting equation is then evaluated using numerical integration. In the special case of infinite visual range (perfectly clear atmosphere), the equation simplifies to the following easily-computed form:

$$P\ [\ acq\ by\ t_2\ ] = 1.0 - \exp\ [\ \frac{-\beta A}{\dot{r}^2\ t_2}\ ] \qquad (2\text{-}4)$$

The basic characteristics associated with the visual target (such as closing rate, target area, or visual range) can be determined from knowledge of the conditions of search. However, the model parameter β can be determined only by observing the performance of pilots in test flights. β can be viewed as a measure of pilot search effectiveness. It reflects the physiological and mental processes underlying pilot performance, and hence can be expected to be considerably different under unalerted and alerted search conditions. The purpose of the unalerted search flight tests was to determine a value of β that best describes pilot performance under unalerted search conditions.

3. TEST FACILITIES AND PROCEDURES

3.1 Subject Pilot Recruitment

Subject pilots were recruited primarily through notices (see Fig. 3-1) posted at active general aviation airfields in eastern Massachusetts and New Hampshire. If the subjects seemed suitable after a telephone screening, they were scheduled for a flight test. A total of 24 general aviation pilots participated. Each pilot completed a pilot history questionnaire (see Appendix A). A summary of selected data from this questionnaire is provided in Tables 3-1 and 3-2.

NOTICE

PILOTS SOUGHT FOR STUDY

The M.I.T. Lincoln Laboratory is seeking subject pilots to participate in a study of VFR workload. Each subject will fly one VFR cross-country mission in a Beech Bonanza while workload data is collected. A test pilot will accompany the subject at all times. As a minimum, subject pilots should possess a private pilot license.

The test aircraft is based at the Lincoln Laboratory Flight Facility at Hanscom Field, Bedford, Massachusetts. Flights will be scheduled Monday through Friday from 0730-1730. Test will be conducted through August of 1986. Each participant should allow approximately 2 hours for pre-flight briefing and flying.

Interested pilots should call Vic Gagnon at 863-5500 (ext. 812-211) for further information.

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Fig. 3.1. Subject recruitment notice.

TABLE 3-1

SUMMARY OF SUBJECT PILOT EXPERIENCE LEVELS

	MINIMUM	MAXIMUM	AVERAGE
age (yr)	21	60	39
Single-engine hours (non-complex)*	210	3800	934
Single-engine hours (complex)	0	5100	789
Multi-engine hours	0	4700	556
Cross-country time (hr) in last 6 mo	2	405	60

*The Beech Bonanza is classified as a complex single-engine aircraft. Pilot single-engine aircraft experience was divided into complex and non-complex hours.

TABLE 3-2

RATINGS HELD BY SUBJECT PILOTS

RATING	FRACTION OF PILOTS HOLDING RATING
Commercial	50.0%
Multi-engine	41.7%
Instrument	58.3%
Certified Flight Instructor	16.7%

3.2 Flight Test Format

Flight tests were conducted between 14 April 1986 and 9 September 1986 at the M.I.T. Lincoln Laboratory Flight Facility located at L.G. Hanscom Field in Bedford, Massachusetts. Each pilot flew a Beech Bonanza aircraft on a triangular cross-country flight of about 45 minutes duration. Two different courses were used (see Figs. 3-2 and 3-3). Subject pilots were accompanied at all times by a safety pilot who sat in the right-hand seat. The safety pilot briefed the subject on the route of flight immediately before leaving the briefing room. A typical text for this briefing can be found in Appendix C.

Three times during the flight the subject aircraft was deliberately intercepted by a Cessna 421 aircraft. All intercepts occurred while the Bonanza was established at cruise altitude during a cross-country flight segment. The Cessna passed at 500 ft altitude separation with as little horizontal offset as could be achieved (normally a few tenths of a mile). Range safety was ensured by constantly tracking each aircraft with a ground radar and requiring that the intercept be aborted if the interceptor failed to visually acquire the subject by 2 nmi range. In addition, the Cessna 421 was equipped with an experimental version of the Traffic Alert and Collision Avoidance System (TCAS). The TCAS traffic advisory display provided additional information to the interceptor regarding the position of the subject aircraft. Special range safety rules can be found in Appendix D. Data from the ground radar was recorded and used in later analysis.

Two techniques were employed to record the time at which the subject saw the interceptor. In the first technique, the safety pilot signalled the time of acquisition by using a remote switch that triggered the SQUAWK IDENT of the aircraft transponder. The time of switch activation could be determined to within ± 3 seconds. In the second technique, the safety pilot used a hand-held stopwatch that had been calibrated with the radar time-of-day clock. Results were checked for reasonableness by comparing radar range at the indicated time of visual acquisition with the safety pilot's estimate of the range at which acquisition occurred.

3.3 Subject Pilot Briefings

A fundamental goal of the testing was to obtain results that closely approximated visual search performance under actual non-test flying conditions. This required great care in the manner in which subject pilots were briefed and treated during the tests. The lack of traffic advisory information alone would prevent subjects from knowing the time or approach direction of traffic. But there was concern that if subjects were told that visual acquisition performance was of primary interest in the test, they would devote undue effort to visual search and thus bias test results. Hence, a briefing procedure was developed that, from the subject's perspective, made it difficult to tell that visual search was any more important to the test than several other aspects of VFR pilotage. It was emphasized that experimenters wanted to see the <u>individual differences</u> in

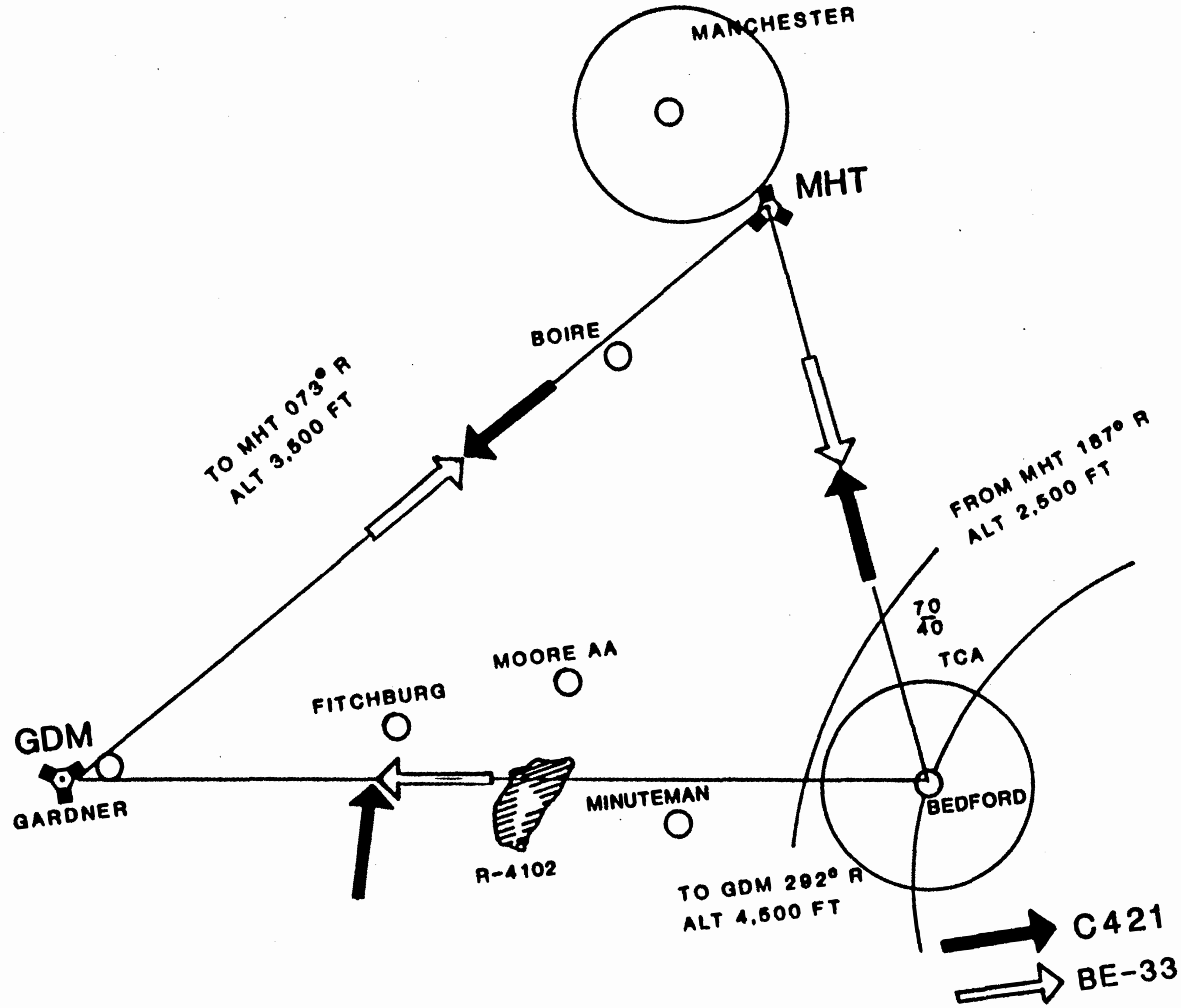

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Fig. 3.2 VFR subject pilot cross country course number 1.

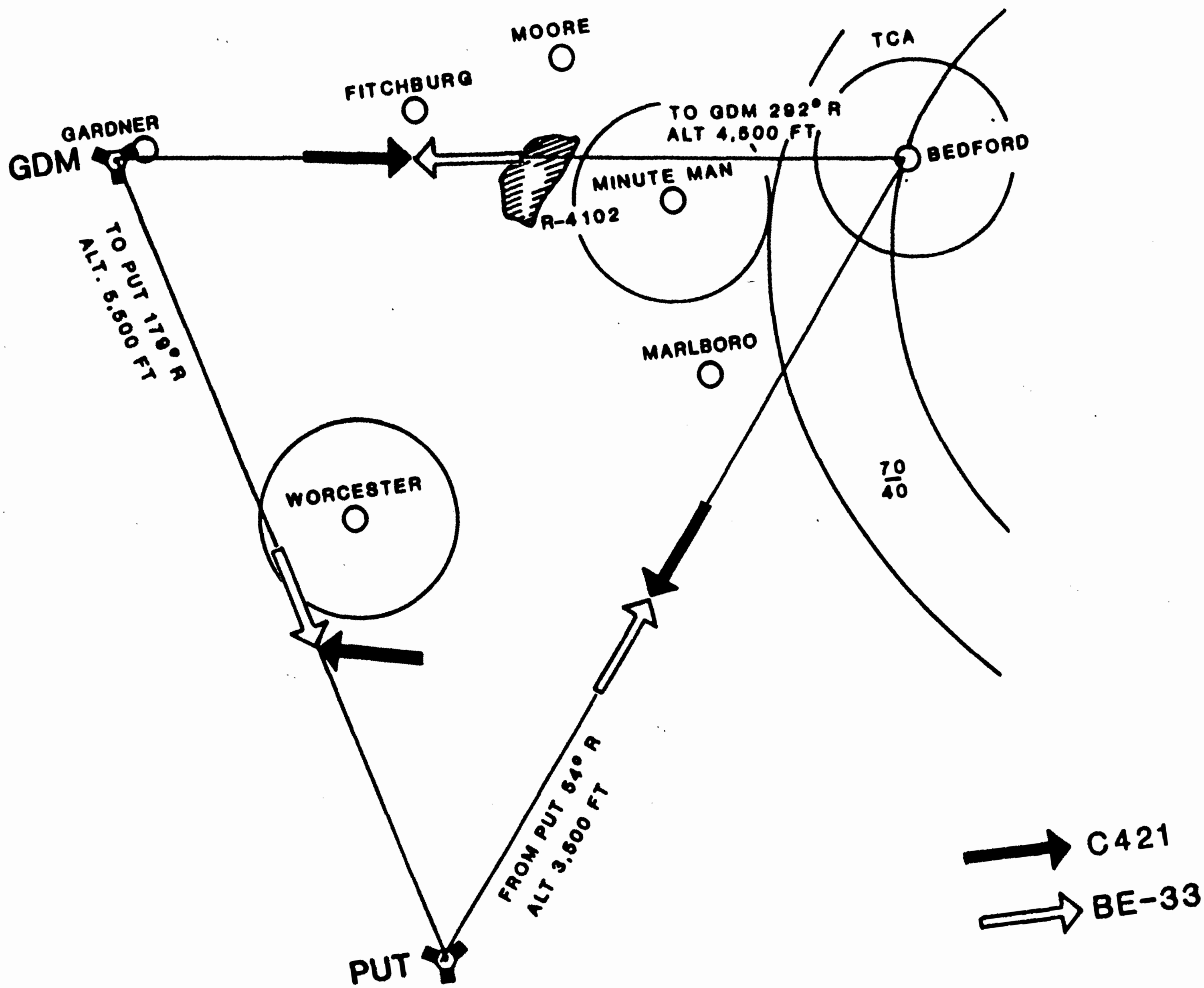

Fig. 3.3 VFR subject pilot cross country course number 2.

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the way pilots approached VFR workload, so subjects should relax and use their own normal flight techniques. Thus, the subjects were given no special reason to concentrate on visual search as opposed to other cockpit duties.

Subjects were not told that intercepts would be conducted for data collection purposes. They were merely told that other company (Lincoln Laboratory) aircraft might be using the same routes, and that if so they would be aware of our altitude and remain separated from us. The text for this procedural briefing is contained in Appendix C. The Cessna 421 interceptor was taxied away from the Flight Facility before the subject pilot was taken out to the ramp.

Subjects were asked to provide three types of data. First, they answered periodic questions asked by the safety pilot (such as "Where is Worcester Airport from our current location?"). Second, they provided workload ratings on a 1-9 scale when requested. Third, they called out all sighted traffic seen as soon as they saw it. The requirement to call traffic was described as a way for experimenters to gather insight into the amount of workload being devoted to visual search in comparison to tasks inside the cockpit.

Most subjects saw the Cessna on only one or two of the intercepts. Only two of the 24 pilots realized during the test that the intercepting Cessna must be another test aircraft. Neither came to this realization until <u>after</u> the third intercept. Hence, the intercepts themselves did not appear to unduly alter the pilot search behavior reflected in the data.

Although every effort was made to put the subject pilots at ease and encourage normal cockpit behavior, it must be assumed that laxity and inattentiveness were discouraged by the very fact that the subjects were flying in a test with a safety pilot who they knew would report on the results of the flight. Thus, it is possible that pilots performed better than they would during actual flight. On the other hand, the increased workload caused by unfamiliarity with the aircraft probably degraded performance for some pilots (see discussion in Section 5). It is felt that overall, the level of pilot visual acquisition performance during the tests approximated that which can be readily achieved in actual flight.

4. DATA ANALYSIS

4.1 Summary of Test Data

Data was obtained for 64 encounters. Basic information concerning these encounters is provided in Table 4-1. Visual acquisition was achieved in 36 of these encounters (56 percent of the total). The median acquisition range for these 36 encounters was 0.99 nmi. The greatest range of visual acquisition was 2.9 nmi.

4.2 Estimation of β for Unalerted Search

In any large set of test encounters, there may exist a few anomalous encounters for which the search conditions differ from those intended in the plan for the experiment. These encounters can cause errors in the estimation of β if they result in visual acquisition that occurs much earlier or later than normal. The technique for estimating β should be relatively insensitive to the presence of anomalous encounters. Although β can be estimated by a maximum likelihood technique (Ref. 1), this technique is sensitive to anomalous encounters and should be applied only if a confident editing of data can be carried out. A more robust technique (described below) has been developed that involves a curve-fitting process that is relatively insensitive to anomalous results.

According to the model, the probability of visual acquisition within any time interval for which β is constant, can be determined from the time integral of the solid angle-contrast product of the target (see equations 2-2 and 2-3). Let this integral be represented by Q. Since Q represents the opportunity for visual acquisition that the target has provided the pilot, Q will be referred to as the "opportunity integral". Then the probability of visual acquisition is

$$P[\text{ acq by t}] = 1 - \text{Exp}[- \beta * Q(t)] \qquad (4\text{-}1)$$

where

$$Q(t) = \int_{-\infty}^{t} \frac{A}{r^2} \text{Exp}\left(\frac{-2.996\ r}{R} \right) dt \qquad (4\text{-}2)$$

TABLE 4-1

ENCOUNTER DATA

Encounter ID	Scenario No.	Visual Range (nmi)	Closing Rate (kt)[a]	Acquisition Range(nmi)[b]	Q (ster-μsec)[c]
101	1	30	- 94.3	-1.00	24.44
102	3	30	-290.4	1.89	8.46
103	3	30	-295.0	0.48	29.77
201	1	12	-189.4	-1.00	175.54
202	2	12	-204.1	1.54	14.13
203	3	10	-284.3	-1.00	8.41
301	1	6	-227.5	0.67	39.32
302	2	8	-280.6	0.47	57.06
401	1	10	-163.0	-1.00	194.40
402	2	10	-251.8	-1.00	111.57
403	3	8	-282.7	0.37	182.88
501	1	10	-204.9	1.74	9.68
601	1	20	-170.3	-1.00	156.25
602	2	20	-290.1	-1.00	45.35
603	3	20	-241.2	0.44	91.04
701	1	20	-187.2	-1.00	137.53
702	2	20	-257.4	-1.00	98.89
703	3	12	-257.6	1.04	16.83
801	1	15	-199.6	1.41	23.67
802	2	12	-270.3	-1.00	85.55
803	3	15	-241.9	-1.00	55.25
901	1	20	-182.4	0.74	49.22
902	2	20	-270.2	0.37	94.82
903	3	20	-290.9	0.99	19.48
1001	1	12	-182.5	0.78	38.04
1002	2	12	-288.4	-1.00	91.06
1003	3	15	-285.6	1.56	7.88
1102	1	15	-291.3	1.01	17.68
1103	2	15	-278.5	1.08	17.20
1201	1	8	-153.7	1.50	16.62
1203	9	8	-232.3	0.85	20.91
1301	1	8	-166.1	1.68	8.98
1302	2	15	-264.6	1.23	15.12
1303	3	12	-201.6	-1.00	21.31
1401	4	5	-289.8	-1.00	69.64
1402	5	5	-285.9	-1.00	36.47
1403	6	5	-251.8	-1.00	87.40
1501	4	20	-246.1	-1.00	85.20
1502	5	20	-260.1	1.09	22.94
1503	6	20	-237.9	-1.00	21.43
1601	4	15	-302.9	1.57	8.90
1602	5	15	-260.8	-1.00	28.81

TABLE 4-1 (CONT'D)

ENCOUNTER DATA

Encounter ID	Scenario No.	Visual Range (nmi)	Closing Rate (kt)[a]	Acquisition Range(nmi)[b]	Q (ster-μsec)[c]
1603	6	15	-261.2	0.49	49.03
1701	4	40	-280.0	-1.00	32.14
1702	5	40	-233.5	2.94	7.17
1703	6	40	-290.6	-1.00	54.32
1801	4	30	-294.4	1.80	8.74
1802	5	20	- 68.7	-1.00	9.13
1803	6	25	-257.5	1.27	17.60
1901	4	50	-282.9	-1.00	102.14
1902	5	50	-206.5	-1.00	62.93
1903	6	50	-190.7	-1.00	32.21
2001	4	20	-298.9	-1.00	43.83
2002	5	20	-279.2	0.32	43.85
2003	6	24	-298.4	2.30	5.70
2101	4	15	-293.3	-1.00	25.26
2102	5	10	-284.1	0.87	26.23
2103	6	10	-253.8	0.68	44.10
2202	5	12	-236.3	0.65	51.49
2203	6	12	-305.7	1.00	112.44
2301	4	12	-273.2	0.32	107.25
2303	6	10	-270.5	0.31	7.70
2401	4	20	-295.3	1.65	8.44
2402	5	20	-268.4	1.34	18.82

[a]Average value

[b]If no acquisition, range is entered as -1.00.

[c]Includes only times prior to range of 0.3 nmi, when target bearing was between 10 and 2 o'clock and target elevation was between -10 degrees and + 10 degrees.

For a given set of experimental data, it is possible to plot the probability of visual acquisition versus Q. Then the value of β most appropriate for that data can be determined by fitting equation (4-1) to the curve. In order to obtain the most robust estimate of β, it is advisable to give heavy weighting to the central portion of the curve (the region centered at 50 percent probability of acquisition). By emphasizing the central region, a natural editing of anomalous data takes place.

In each experimental encounter, Q starts at zero and increases until the encounter terminates. The encounter is terminated whenever visual acquisition occurs. It can also be terminated for artificial reasons (e.g., the target passes outside the field of view, the encounter is aborted, etc). When an encounter terminates prior to visual acquisition, then that encounter provides data only for values of Q up to the final value observed. This is because it is not known whether or not acquisition would have occurred if the trial had continued. When an experiment terminates in visual acquisition, then it can be applied to the entire range of Q values.

In computing Q values for Table 4.1, the integration was terminated if

1) visual acquisition occurred,

2) the intruder passed outside the prime search area (defined as bearings from 10 o'clock to 2 o'clock and elevation angles from -10 to +10 degrees), or

3) the target came within 0.3 nmi of own aircraft.

The first criterion is obvious, but the second two criteria are artificial ones. Criterion 2 limited the β estimate to the angular region normally searched by pilots. This is the region most likely to contain threat aircraft. Criterion 3 reduced the sensitivity of the estimate to minor errors in recording the time of visual acquisition (because the size of the aircraft is growing rapidly for ranges less than 0.3 nmi, a slight error in determining the time of visual acquisition can result in a large error in Q). In estimating β values, acquisitions that occurred after the termination of the Q integration must be ignored. Note that as long as the model is valid, the application of arbitrary termination criteria reduces the amount of data available, but does not bias the estimated value of β for targets within the prime search area. It should be noted however, that if an aircraft is approaching from outside the prime search area, the value of β derived from Table 4-1 will probably prove to be too great.

The lower curve in Fig. 4-1 shows the results of fitting equation (4-1) to the unalerted search data in Table 4-1. It can be seen that good agreement between experimental results and theory is obtained for a β value of approximately 17000/ster-sec.

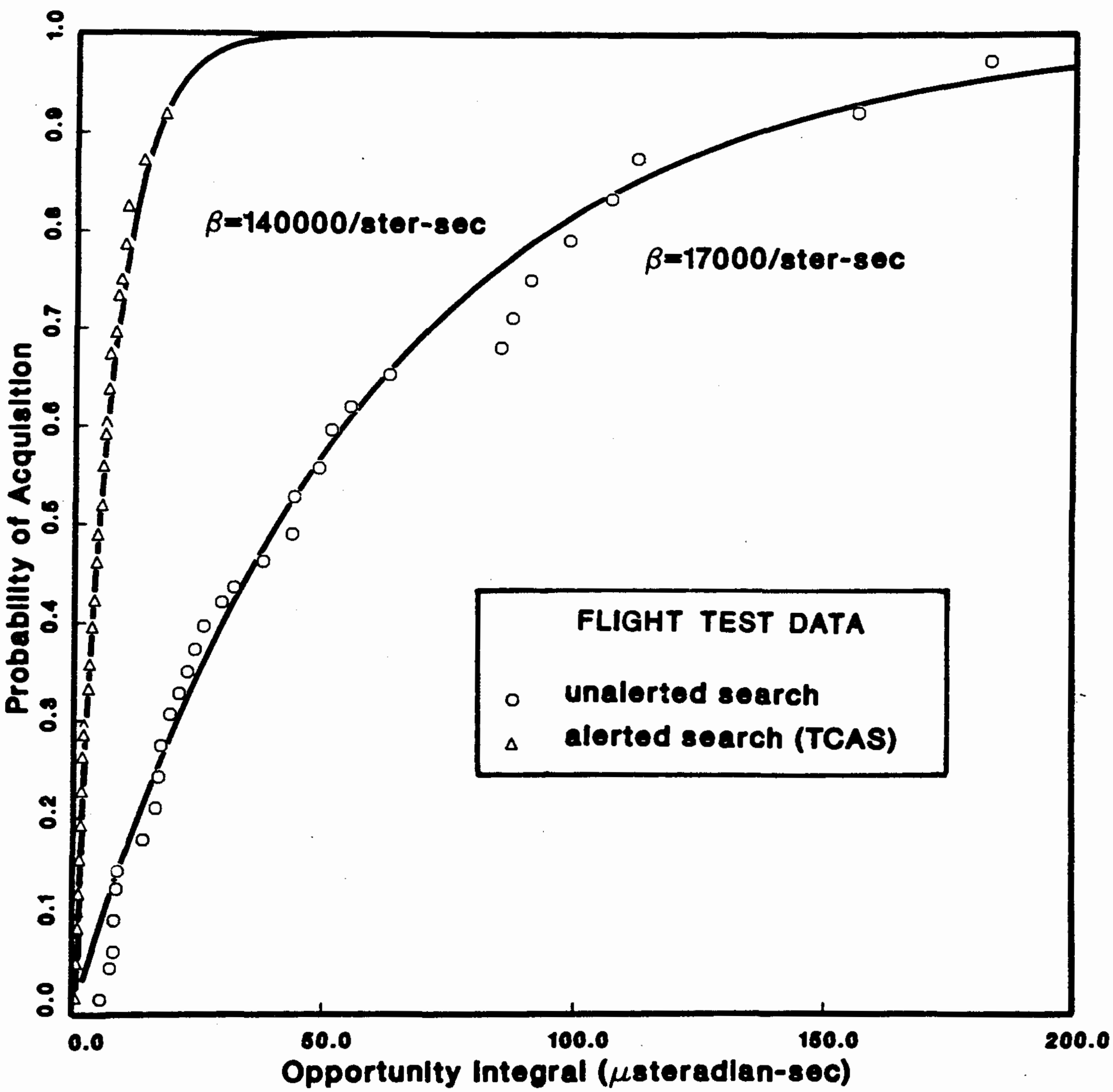

Fig. 4-1. Theoretical curves are fit to flight test data to determine an appropriate value of β.

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Table 4-2 provides model predictions of visual acquisition performance using the above result. Here β is set to 17,000/ster-sec and the probability of visual acquisition is tabulated in 6 sec increments. It is assumed that visual search begins either three minutes before collision or when the size of the target exceeds 1 minute of arc (whichever occurs last). The exact time of search initiation has little impact upon the calculations as long as it is three or four times the time of evaluation.

TABLE 4-2

VISUAL ACQUISITION PREDICTIONS FOR UNALERTED SEARCH
(Target size = 70 sq. ft.)

	Probability of Visual Acquisition by t seconds to collision				
Closing Rate (kt)	240	120	240	360	240
Visual Range (nmi)	10	20	20	20	300
t					
6.00	0.5621	0.9854	0.6148	0.3204	0.6690
12.00	0.2693	0.8515	0.3281	0.1384	0.3964
18.00	0.1505	0.6860	0.2003	0.0741	0.2631
24.00	0.0920	0.5485	0.1320	0.0432	0.1861
30.00	0.0593	0.4422	0.0909	0.0259	0.1363
36.00	0.0394	0.3604	0.0641	0.0151	0.1016
42.00	0.0265	0.2968	0.0457	0.0081	0.0761
48.00	0.0179	0.2466	0.0324	0.0032	0.0565
54.00	0.0119	0.2063	0.0226	0.0000	0.0411
60.00	0.0077	0.1735	0.0151	0.0000	0.0286

4.3 Comparison to Alerted Search

For purposes of comparison, a similar analysis was conducted using data from the flight testing (Ref. 2) of the Traffic Alert and Collision Avoidance System (TCAS). The result is shown in the upper curve in Fig. 4.1. It can be seen that a β value of 140,000/ster-sec results produces a good fit. This indicates that the TCAS traffic advisory increased β by a factor of approximately eight (i.e., one second of search with the aid of a TCAS traffic advisory is as effective as 8 seconds of unalerted search).

5. FURTHER RESULTS

5.1 Examination of Pilot Differences

It was not the purpose of the tests to measure or explain the differences in visual acquisition performance between pilots. The goal of the experiment was to determine a β value that applied <u>on average</u> to the 24 pilots tested. Because each subject could be exposed to only three encounters, a reliable determination of β for an individual pilot was impossible. The random nature of the visual acquisition process leads to individual β values that are far above and below the value that would be derived from a larger quantity of data. However, by grouping pilots together in terms of common characteristics, it is possible to determine if any strong correlations exist between recorded pilot characteristics (such as age or experience) and visual acquisition performance.

An estimated β value was calculated for each pilot by dividing the number of visual acquisitions achieved by the sum of the opportunity integrals, Q, in all encounters flown by that pilot. For instance, pilot No. 1 had 2 visual acquisitions in three encounters with Q values of 24.44, 8.46, and 29.77 ster-μsec (see Table 4.1 for data). This produces an estimated β value for pilot No. 1 of

$$\frac{2\mathrm{x}10^{6}}{22.44 + 8.46 + 29.77} = 31913/\text{ster-sec.}$$

It should be noted that any visual acquisitions that occurred after the cut-off range of 0.3 nmi was reached are not to be counted in the above process.

The linear correlation coefficient that exists between the β scores of pilots and the pilot background characteristics (see Appendix B) are shown in Table 5.1. The most positive correlations noted were with instrument rating, CFI rating, and single-engine hours. These correlations indicate that pilots who were most capable in flying the aircraft also performed better in visual search. It could be inferred that the workload involved in merely flying the aircraft detracts from the visual search capability of low-time, inexperienced pilots. The most negative correlations noted were with age and workload factors. (The negative correlation with multi-engine hours is probably explained by the fact that a high value of such hours was strongly correlated with age).

During the flight, the test pilot estimated the fraction of time the subject spent looking outside the cockpit. The fraction varied from 0.35 to 0.90 with an average value of 0.60. Surprisingly, there was little correlation of β with this fraction ($\rho = -0.004$). This may indicate that only a fraction of the time spent looking outside the cockpit was actually being spent in a productive search for traffic.

In debriefing, subjects were asked whether they thought that the emphasis they had placed upon visual search during the test had been more or less than in normal flight. There was little correlation of their answers with their observed performance ($\rho = 0.015$). This is one indication that visual search emphasis did not strongly bias test results.

TABLE 5.1

LINEAR CORRELATION COEFFICIENT OF PILOT
β SCORE WITH SELECTED VARIABLES

Correlation Coefficient	Variable
0.372	instrument rating
0.350	CFI rating
0.254	SE hours (non-complex)
0.208	sky conditions
0.195	use of sunglasses
0.182	commercial rating
0.162	XC time last 6 mo.
0.133	use of visual landmarks
0.112	familiarity with Beech Bonanza
0.104	Avg. score on pilotage questions
0.015	emphasis on visual search
-0.004	% time looking outside cockpit
-0.070	technique
-0.188	SE hours (complex aircraft)
-0.216	ME hours
-0.241	military flight training
-0.284	workload rating (avg.)
-0.349	age
-0.385	aircraft impact

To further analyze performance, a stepwise linear regression analysis was applied to the data. This analysis indicated that age and SE hours were the two most important variables in predicting a pilot's β score. The equation for predicting β was

$$\hat{\beta} = 59225 - 1211*(\text{age}) + 13.58 * (\text{SE hours})$$

This equation produced an R-squared value of 0.276, indicating that β-scores could not be predicted very precisely from pilot background.

5.2 On the Difficulty of Visual Acquisition on Extremely Clear Days

Two experiences during the flight test program suggested that special visual acquisition difficulties may be associated with extremely clear days. One day, while a subject pilot flight was being conducted, a mid-air collision between a helicopter and a small fixed-winged aircraft occurred only 15 miles north of the test area. It seemed an ironic fact that this accident occurred on an exceptionally clear day. Two weeks later, on another exceptionally clear day, all three planned intercepts had to be aborted because the intercepting aircraft failed to visually acquire the subject prior to the required 2 nmi range. These experiences suggested that visual acquisition could be more difficult on exceedingly clear days than on days with normal visibility. The probable explanation for this, and the consequences for visual performance modeling, are discussed below.

The conspicuousness of a visual target increases as its contrast with its background increases. This contrast is dependent upon the scattering properties of the aircraft (paint scheme, surface reflectances, etc.) and environmental visual conditions (sunlight illuminance, visual range, clouds, etc.). Scattering that occurs between the eye and the target reduces the inherent contrast of the target. It has been found that if the contrast is reduced to approximately 5 percent, the target disappears into the background. The range at which this occurs for a target that would otherwise have 100 percent contrast is used as a measure of the visual range.

Experience shows that for small aircraft on collision courses, most visual acquisitions will occur at ranges of one to two miles. As long as the visual range is two or three times this distance, the scattering that occurs between the eye and the target has little effect upon visual acquisition capability. However, the scattering that occurs behind the target can still be significant since it determines the brightness of the background. Normally, there is a milky band of haze near the horizon. This haze is significantly brighter than the zenith sky. Most aircraft near enough to own altitude to pose a collision risk will approach with this haze as background. This is fortunate, since the increased contrast makes aircraft easier to see. On exceedingly clear days, the horizon haze layer disappears and the sky background is appreciably darker. This reduces the target contrast, making visual acquisition more difficult.

Similar comments apply to aircraft that approach with terrain as the background. The terrain is significantly darker than the sky. Under hazy conditions, targets that are only slightly below own altitude are seen against distant terrain that is receding into the haze. This can provide a brighter background that enhances contrast. Haze has the added advantage of obscuring small-scale ground features that might make the image of the target difficult to perceive.

The visual acquisition model described in section 2 takes into account the degradation in visual acquisition capability due to scattering between the eye and the target. But it does not reflect any degradation that might occur due to background darkening under exceptionally clear conditions. Since such atmospheric conditions were unusual during the flight tests described in this document, the results are not significantly affected by this limitation of the model. However, it should be recognized that the results are optimistic when applied to situations where extremely clear conditions prevail.

REFERENCES

1. Andrews, J.W., "Air-to-air Visual Acquisition Performance with Pilot Warning Instruments (PWI)", Project Report ATC-73, Lincoln Laboratory, M.I.T., (25 April 1977), FAA-RD-77-30.

2. Andrews, J.W., "Air-to-air Visual Acquisition Performance with TCAS II", Project ATC-130, Lincoln Laboratory, M.I.T., (27 July 1984), DOT/FAA/PM-84/17.

APPENDIX A

DATA COLLECTION FORMS

A.1 Pilot Background Questionnaire

CONFIDENTIAL INFORMATION

VFR FLIGHT TEST
MIT LINCOLN LABORATORY

PILOT BACKGROUND QUESTIONNAIRE

NAME : ______________________________ TEL : ________________________

ADDRESS : ____________________________

____

____

AGE : ________ YEARS AS PILOT : ______

RATINGS HELD : ____

Any military flight training? _____ yes _____ no

AIRCRAFT EXPERIENCE (HOURS):

Single-engine __________________ Complex ____________________

Multi-engine ___________________

How much cross-country time in last 6 months?: ______________ hours

Operated at Hanscom Field in last 6 months?: _____ yes _____ no

Aircraft have had most time in (last 6 months): ________________(make/model)

Flown Beech Bonanza in last 6 months?: ______ yes _____ no

Familiar with use of HSI? _____ no ____ somewhat ____ yes

Familiar with use of DME? _____ no ____ somewhat ____ yes

Have current FAA medical certification? _____ yes ____ no

THANK YOU

A.2 Safety Pilot In-flight Questionnaire

DATE ______________ AM/PM

CONFIDENTIAL INFORMATION

VFR FLIGHT TESTS

Q#________	G / F / P	Q#________	G / F / P
Q#________	G / F / P	WL________	
WL________		Q#________	G / F / P
Q#________	G / F / P	Q#________	G / F / P
WL________		Q#________	G / F / P
Q#________	G / F / P	WL________	
Q#________	G / F / P	Q#________	G / F / P
WL________			

TRAFFIC SEEN (O = self only, √ = subject first, ⊘ = self, then subject)

ENCOUNTERS (PTI = prior to intercept) ENC #

	1	2	3
Range of Visual	______ nmi	______ nmi	______ nmi
Workload PTI (1-9)	________	________	________
Distractions PTI (0 = none, 1 = possibile 2 = definite)	0 / 1 / 2	0 / 1 / 2	0 / 1 / 2
Flight visibility (intercept direction)	______ nmi	______ nmi	______ nmi
Visual background PTI (sky, cloud, haze, terrain)	________	________	________
Earlier intercept affected?	Y / ? / N	Y / ? / N	Y / ? / N
Wind aloft	________	________	________
Other factors:			

SAFETY PILOT QUESTIONNAIRE (CONT'D)

1. Pilot familiarity with airplane during XC:

inadequate / poor / acceptable / good / excellent

2. How heavily did pilot rely upon visual landmarks to navigate?

not at all / slightly / moderately / heavily

3. Time spent in visual search on XC : __________ per cent

4. Search in directions other than 12 o'clock on XC:

never / rarely / occasionally / regularly

5. Did pilot wear sunglasses on XC? ____ yes ___ no

6. Did pilot's overall flight technique appear normal, given his background and experience level?

no / fairly / yes

If not, explain how it differed from normal:

Safety Pilot ____________________

A.3 Debriefing Questionnaire

DEBRIEFING FORM

VFR FLIGHT TEST

Prior to coming to Lincoln Laboratory, had you discussed this flight test with any previous subject pilot?

____ yes ____ no

How much did unfamiliarity with the aircraft increase your workload while flying the cross-country course?

not at all / slightly / significantly

During the cross-country portion of this flight, did you give more or less attention than you normally would to any of the following aspects of flight. Please give thoughtful and honest consideration to artificial factors such as your knowledge that you were in a test, presence of the safety pilot, it wasn't your normal aircraft, etc.:

	Somewhat Less	About the Same	Somewhat More
fuel management	______	______	______
navigation	______	______	______
visual search for traffic	______	______	______
holding altitude	______	______	______
holding course	______	______	______
weather	______	______	______

Any other comments? :

THANK YOU!

APPENDIX B

SUBJECT PILOT DATA BASE

Selected background information on the 24 subject pilots was compiled in a computer data base. A list of the variables and the coding used is provided in Table B-1. The data base itself is provided in Table B-2. In addition to data collected from the pilot background questionnaire, the table contains some descriptive data collected during the flight test.

TABLE B-1

VARIABLES USED TO DESCRIBE PILOTS

Variable	Description
date	date of flight
age	years
comm rating	0=no, 1=yes
ME rating	0=no, 1=yes
instr rating	0=no, 1=yes
CFI rating	0=no, 1=yes
SE hours	total hours in non-complex single-engine aircraft
complex hours	total hours in complex single-engine aircraft
ME hours	total hours in multi-engine aircraft
XC time	Cross-country hours in last 6 months
Bonanza	0=have not flown Bonanza in last 6 months, 1= have flown Bonanza in last 6 months
mil training	0=no, 1 = yes
fam w/AC	0=inadequate, 4=excellent
AC workload	0=not at all, 1=slightly, 2=significantly
landmark nav	0=not at all, 3=heavily
% vis search	percent of time devoted to visual search
sunglasses?	0=not worn, 1=worn
technique normal	0=no, 1=fairly, 2=yes
sky condition	1=clear, 2=scattered, 3=broken, 4=lt. overcast, 5=heavy overcast
avg workload	0-90 in tenths of a unit
visuals first	traffic seen first by subject
visuals second	traffic seen first by safety pilot, second by subject
visuals missed	traffic seen only by safety pilot
emphasis visual	1=less, 2=same, 3=more
avg q score	average score on in-flight questions (10=poor, 20=fair, 30= good)

TABLE B-2

SUBJECT PILOT CHARACTERISTICS

Subject No.	1	2	3	4	5	6	7	8	9
date	4/14AM	4/14PM	4/15PM	4/16AM	4/16PM	4/18AM	4/18PM	4/22AM	4/22PM
age	38	48	42	32	28	24	25	40	40
comm rating	1	1	1	0	1	0	1	1	0
ME rating	1	0	0	0	1	0	0	0	0
instr rating	1	1	1	0	1	0	1	0	0
CFI rating	1	1	0	0	1	0	1	0	0
SE hours	675	1450	1350	250	800	240	450	450	450
complex hours	200	220	1600	1	850	8	20	8	250
ME hours	25	20	250	0	300	0	2	0	0
XC time	5	10	75	60	100	10	35	3	15
Bonanza	0	0	1	0	1	0	0	0	0
mil training	0	0	1	0	0	0	0	0	0
fam w/AC	4	2	4	2	4	2	3	1	3
AC workload	1	2	0	1	0	1	1	1	1
landmark nav	2	1	1	1	2	1	1	0	2
% vis search	80	55	60	40	60	35	60	65	70
sunglasses?	1	1	1	0	0	0	0	1	0
technique normal	2	2	2	2	2	2	3	2	2
sky condition	4	3	1	3	5	2	1	2	3
avg workload	44	56	34	42	32	60	46	58	40
visuals first	1	2	5	1	1	0	3	5	4
visuals second	3	3	2	2	3	2	2	2	3
visuals missed	5	3	2	7	1	4	1	0	5
emphasis visual	3	1	3	2	3	2	3	2	2
avg q score	26	30	30	26	29	27	29	24	29

(Table continued)

TABLE B-2

SUBJECT PILOT CHARACTERISTICS (CONT'D)

Subject No.	10	11	12	13	14	15	16	17	18
Date	5/14PM	5/15PM	5/27PM	5/28PM	5/30PM	6/3PM	6/4PM	6/26PM	6/30PM
age	44	49	26	42	38	43	30	60	21
comm rating	0	0	1	0	0	1	0	1	0
ME rating	0	1	1	0	0	1	0	1	1
instr rating	0	1	1	0	0	1	0	1	1
CFI rating	0	1	0	0	0	1	0	0	1
SE hours	360	3800	650	450	210	1600	300	1000	600
complex hours	200	500	65	60	20	430	50	5000	90
ME hours	0	325	56	0	0	12	20	4700	11
XC time	20	25	135	50	85	30	2	10	30
Bonanza	0	1	0	0	0	1	0	0	0
mil training	0	0	0	0	0	0	0	1	0
fam w/AC	3	1	2	2	3	2	2	2	3
AC workload	1	0	1	1	1	1	0	1	1
landmark nav	1	1	1	1	2	1	3	2	2
% vis search	50	45	50	40	70	55	65	60	65
sunglasses?	0	1	1	1	0	1	1	1	1
technique normal	2	2	2	1	2	2	2	2	2
sky condition	1	1	0	0	0	0	0	0	0
avg workload	42	52	52	58	58	40	56	40	48
visuals first	4	3	1	1	0	2	3	0	2
visuals second	1	1	1	1	1	0	0	1	2
visuals missed	1	2	2	0	4	1	1	1	4
emphasis visual	3	3	2	2	2	3	3	3	1
avg q score	27	25	29	29	30	28	26	29	30

(Table continued)

TABLE B-2

SUBJECT PILOT CHARACTERISTICS (CONT'D)

Subject No.	19	20	21	22	23	24	AVG
Date	7/1PM	7/8PM	7/9PM	7/22	7/24PM	9/9PM	
age	48	57	29	48	53	32	39.04
comm rating	0	1	1	0	0	1	0.50
ME rating	0	1	1	1	0	0	0.42
instr rating	0	1	1	1	0	1	0.58
CFI rating	0	1	0	1	0	1	0.42
SE hours	340	2000	2050	900	650	1400	934.37
complex hours	30	3000	1200	5100	0	40	789.25
ME hours	0	2500	525	4600	0	5	556.29
XC time	10	120	405	65	50	100	60.42
Bonanza	0	1	1	0	0	0	0.25
mil training	0	1	0	1	0	0	0.17
fam w/AC	2	4	4	3	1	2	2.54
AC workload	1	0	1	2	2	1	0.92
landmark nav	2	1	2	3	1	2	1.50
% vis search	90	45	70	75	60	80	60.21
sunglasses?	1	1	0	0	0	1	0.58
technique normal	1	2	2	2	2	2	1.96
sky condition	0	-	-	-	-	-	1.37
avg workload	46	44	42	40	70	32	47.17
visuals first	2	1	2	3	0	16	2.58
visuals second	2	1	2	0	5	0	1.67
visuals missed	1	3	1	1	0	4	2.25
emphasis visual	3	3	1	2	1	2	2.29
avg q score	28	27	30	30	27	29	28.08

APPENDIX C

SUBJECT PILOT BRIEFINGS

C.1 Procedural Briefing

[Note: This briefing was given when the subject first arrived at the briefing room. It describes the purpose of the test and the data collection procedures required of the subject.]

Introduction

This briefing will cover the objectives of the test and our data collection procedures. Afterwards, our safety pilot will brief you on the route of flight, the weather, and so forth.

Test Objectives

This study is being carried out by Lincoln Laboratory under the sponsorship of the FAA. Its purpose is to add to our knowledge concerning how VFR pilots actually fly in <u>normal</u> operations (as opposed to a check flight or an emergency situation). We want to determine how you allocate your workload resources: which tasks you work hard at, which you let slide, which bits of information you have available for immediate recall and which you would have to look up if you needed them.

We expect to see differences among pilots depending upon training, background, and the individual style of the pilot. It is the range of variations in cockpit technique that interests us. Therefore, it is important that, insofar as possible in an experimental environment, you relax and fly using your normal cockpit "style" and level of effort. Our safety pilot will give you any assistance you need to feel comfortable with the aircraft, but the flight is basically single-pilot.

Data Collection

Data will be gathered in several ways by the safety pilot who accompanies you.

First, there are formal questions. At random intervals, the safety pilot will say "question" and then ask you some question relative to the flight. You should answer these questions promptly, giving your best guess if you're not sure of the answer. These questions are designed to tell us what you have been paying attention to, what you have ignored, and so forth. You aren't expected to know the answers to all of the questions (in fact, you may feel that some of the questions are rather irrelevant to the flight). But your answers will tell us something about your allocation of attention.

Secondly, there are workload ratings. The safety pilot will occasionally say "How's your workload, now?" You should then rate your overall workload level on a 1-9 scale with 5 being average (see hand-out). The exact interpretation of each number is not so important (it's OK if your "6" is what some other pilot would call a "7"). We are most interested in the relative changes you perceive in the workload during the course of the flight.

As the last item, we want you to call out all sighted traffic as soon as it is sighted (even if at a great distance and clearly no factor). That is, point it out even if its an airliner at 30 thousand feet or just a speck on the horizon. This helps us understand the amount of effort you are devoting to visual search in comparison to tasks inside the cockpit. You should start calling traffic as soon as you are outside the traffic pattern. Since we won't prompt you on this (we won't say "Did you see that aircraft that just passed us?"), its up to you to just get in the habit of pointing out all the traffic.

POST FLIGHT

After the flight you will be asked to complete a short one-page questionnaire about the flight. And that will complete the test.

Naturally, all data we collect is confidential in the sense that no subject pilot's name will be attached to any data that is released.

SAFETY

Naturally, flight safety comes first and will not be compromised by any test procedures.

Although the safety pilot will normally provide you with only minimal assistance, he remains the pilot-in-command and should any event bring the safety of the flight into question he may take control of the aircraft until the problem is resolved.

Lincoln Laboratory operates its own radar facility to assist with company operations. The radar should be up this afternoon. If so, we will check in with them to let them know what we're doing. If there are other company operations in the area, they will be kept clear of our altitudes. We will not request any radar services from the radar site. As far as you are concerned, you are on a cross-country VFR flight without any ATC contact.

Here is a summary of the procedures. (See hand-out).

Any questions about the data collection procedures before I turn it over to our safety pilot?

C.2 Pre-flight Briefing on Route of Flight

[Note: This briefing was given by the safety pilot immediately prior to leaving the briefing room for the aircraft. This is a typical text. The actual text employed was, of course, adapted to the prevailing weather and the degree of familiarity of the pilot with the area.]

This is a cut-out from a sectional chart showing our route of flight [show hand-out chart]. You can take this with you in the aircraft if you wish. We will depart Hanscom Field on Runway 11, making a right hand departure to intercept the 292° radial to the Gardner VOR. We will climb to 4500 ft.

The floor of the Boston TCA extends to 20 nmi at 4000 ft. We will have to stay under the floor until we reach 20 nmi. We shouldn't have any problem with that.

The Turner drop zone extends to 3995 at this location [point out]. We should be above that altitude.

We will cruise at an airspeed of 150 knots until reaching the Gardner VOR.

The aircraft is equipped with dual comm. One radio we will keep tuned to our company frequency. The other you can use as you desire. Normally, we monitor Boston approach control during the first leg of the flight.

Upon reaching Gardner, we will then turn to fly the 73 degree radial to the Manchester VOR, and will descend to 3500 ft for that leg of the flight.

We will be just outside the Manchester airport traffic area [point out]. Normally, we monitor Manchester approach control while in the vicinity of Manchester.

Out of Manchester we will turn to the 170 degree radial and descend to 2500 ft. We will maintain 2500 until we pass the city of Lowell [point out].

Then we will tune in the Hanscom ATIS and then contact Hanscom tower. If congestion makes it necessary, we can do one or two 360° turns here [point out] to delay our arrival at Hanscom.

The weather today is 6000 scattered. Winds are 260° at 25 knots. These are the current reports from Manchester, Concord, and Hanscom [show pilot weather summaries received by wire].

We can listen to the current ATIS now. We will listen to it again when we are in the aircraft. [Listen to Hanscom ATIS on portable radio].

I have some other things to say about the aircraft, but I'll wait until we are in the cockpit so that I can point to the guages.

Any questions?

C.3 Debriefing

[Note: The following material was used in the post-flight debriefing.]

Do you have any suggestions for improving our briefings? Any suggestions for making you more comfortable in the aircraft?

Please do not provide potential future subjects with any details on the flight test.

APPENDIX D

TEST SAFETY PROCEDURES

Special Safety Rules for VFR Subject Pilot Missions

The following special safety rules will be observed in VFR subject pilot missions requiring interception of a subject pilot. They apply in addition to normal Group 42 safety rules.

1. Subject/interceptor altimeters will be checked in flight if any avionics modifications or disassembly has occurred that could affect the calibration. In addition, altimeters will be checked if more than 5 days have passed since the last visual confirmation of accuracy.

2. For each intercept at least 500 feet altitude separation must be maintained unless both of the following conditions are true:

   a) altimetry accuracy was visually confirmed by in-flight observation earlier in the mission

   b) the interceptor has visual contact with the subject

3. An intercept will be aborted if any of the following conditions is true:

   a) MODSEF is unable to provide radar traffic advisories

   b) the interceptor fails to establish visual contact by the time the aircraft are reported to be 2 nmi apart

   c) visual contact is lost within 2 nmi range

   d) a non-test aircraft is judged to be a factor that constrains the encounter

4. Whenever test procedures allow, observers and equipment operators will assist flight crews in visual search for traffic during encounters.