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FLIGHT TEST EVALUATION AND ANALYSIS OF AN OPTICAL IR PWI SYSTEM

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16. Abstract This report documents the flight test results of the optical infrared (IR) Pilot Warning Instrument (PWI) system conducted by the Transportation Systems Center as part of an FAA/NASA PWI development program. The test program is described and the flight test data presented. The data is analyzed and used to calibrate a model that is developed to characterize the system performance. The cumulative probability of detection versus range for a given system threshold is calculated and compared with the PWI performance specification defined by the Collision Prevention Advisory Group (COPAG). The comparison indicates that the Optical IR PWI system tested met the COPAG specifications for a detection likelihood of 95% for a 1 nmi range for an appreciable fraction of the testing time. Even under the worst testing conditions encountered, the range at which this detection likelihood occured was sufficiently large to demonstrate feasibility and to recommend a continuation of the development effort for this approach. A series of recommendations for improving system performance and obtaining additional information needed to characterize that performance are included.

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PREFACE

Optical infrared Pilot Warning Instrument test and evaluation described in this report was planned and conducted by the Transportation Systems Center PWI Program Office. Experimental PWI systems tested were developed at the former National Aeronautics and Space Administration Electronic Research Center. The principal objective of this program is to conduct analysis of PWI systems. Optimum system configurations are investigated and developed through flight tests and experimental development. The PWI program was sponsored by the NASA, Office of Advanced Research and Technology, Washington, D.C.

Flight test of the PWI system was performed by the Federal Aviation Administration National Aviation Facilities Experimental Center, Atlantic City, New Jersey. The authors wish to express their sincere gratitude for the continuing support rendered to the TSC team by the various NAFEC organization units and individuals in all phases of this test. At the same time, the invaluable assistance given to TSC by Mr. George Rock and Mr. M. Lewis of LORAL Corporation and the significant contributions made by Daniel DeCrhistoforo, Arthur E. Foley, Lawrence McCabe, Robert Rudis and Dr. Frank Tung toward the success of this effort are gratefully acknowledged.

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1.0 INTRODUCTION

The Collision Prevention Advisory Group (COPAG) whose members are representatives of airspace user organizations and government agencies, including DOT, NASA and DOD under the chairmanship of the FAA, defined the need for developing an inexpensive Pilot Warning Instrument (PWI) to assist general aviation pilots in *"seeing and avoiding"* other aircraft. An optical (IR) PWI, based on the detection of xenon strobe anti-collision beacons, was developed at NASA's Electronic Research Center (ERC)[1,2,3]. Prior to the closing of the center in June, 1970, two prototype systems were subjected to limited flight tests[4].

With the forming of the Transportation Systems Center under the Department of Transportation, the PWI effort was renewed with NASA and FAA funding. Emphasis was changed from developing and evaluating specific hardware systems to evaluating the capacity of the IR system concept to meet PWI requirements generated by COPAG. This concept was to be compared with other PWI approaches in various stages of definition and development.

This report presents the flight test results and analysis of the optical IR PWI system conducted by TSC as the final portion of the overall NASA funded effort. The FAA portion of the program is continuing and will use these results and other studies to further evaluate and compare optical IR PWI with other PWI approaches.

2.0 PWI SYSTEM DESCRIPTION

2.1 GENERAL REMARKS

The PWI prototype hardware used in the flight tests has been described in detail in several reports and papers[4,5,6].

A summary equipment description is included here to enable the reader to understand and appreciate the test results in terms of the various contributing factors.

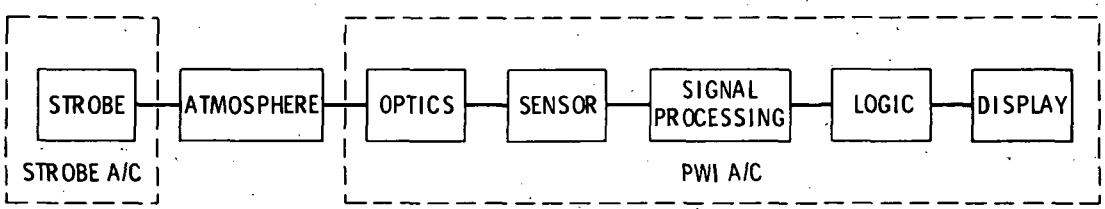


Figure 1. IR PWI System

Figure 1 depicts the various components both hardware and environmental which characterize the optical IR PWI system. These blocks are discussed briefly below with respect to their pertinent features.

2.2 AIRCRAFT STROBE BEACON

The signal source used in the flight tests was a xenon strobe light. The light output was radiated in a beam of about ±10° in elevation and 360° in azimuth, (Figure 2). In the tests, this lamp was mounted below the fuselage of the "strobe aircraft".

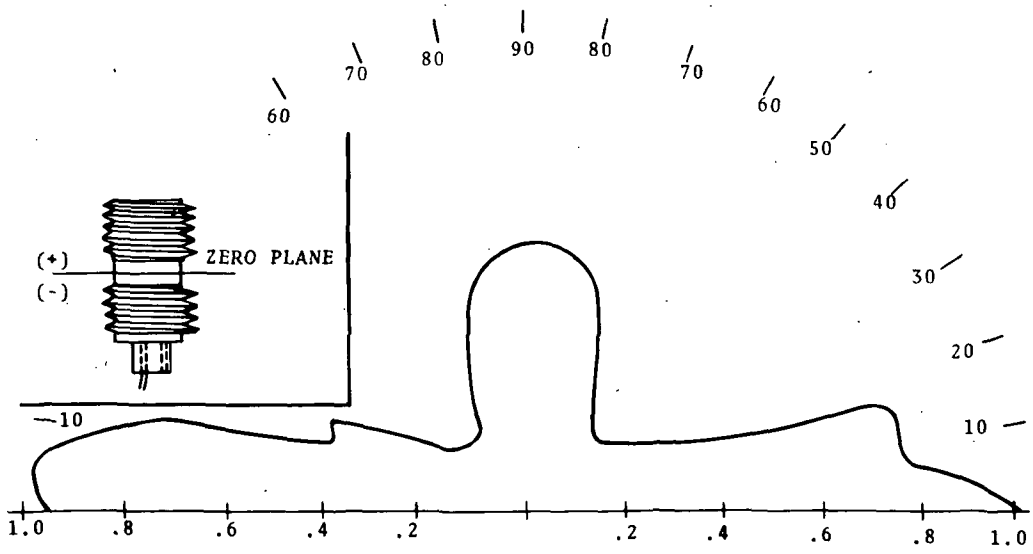


Figure 2. Whelen Strobe Light Characteristics

The signal radiated by the lamp is produced by a capacitive discharge of approximately 20 joules. The resulting light pulse has a rise time of 25 to 40 microseconds, a duration of 200 microseconds and a peak intensity of some 1200 watts per steradian in the near IR. It is produced at a repetition rate of about 55 flashes per minute (the specified limits on flash rate for this type of lamp are 40 to 80 flashes per minute). The average dc aircraft power required is 50 watts. Data on the aircraft strobes were obtained under a TSC study contract by the Draper Laboratory of MIT[7].

The radiation received and processed by the optical IR PWI system lies in the near infrared region of the electromagnetic spectrum. The detailed distribution of energy within this region is shown in Figure 3. The spectral power available from the lamps is selectively attenuated by the atmosphere.

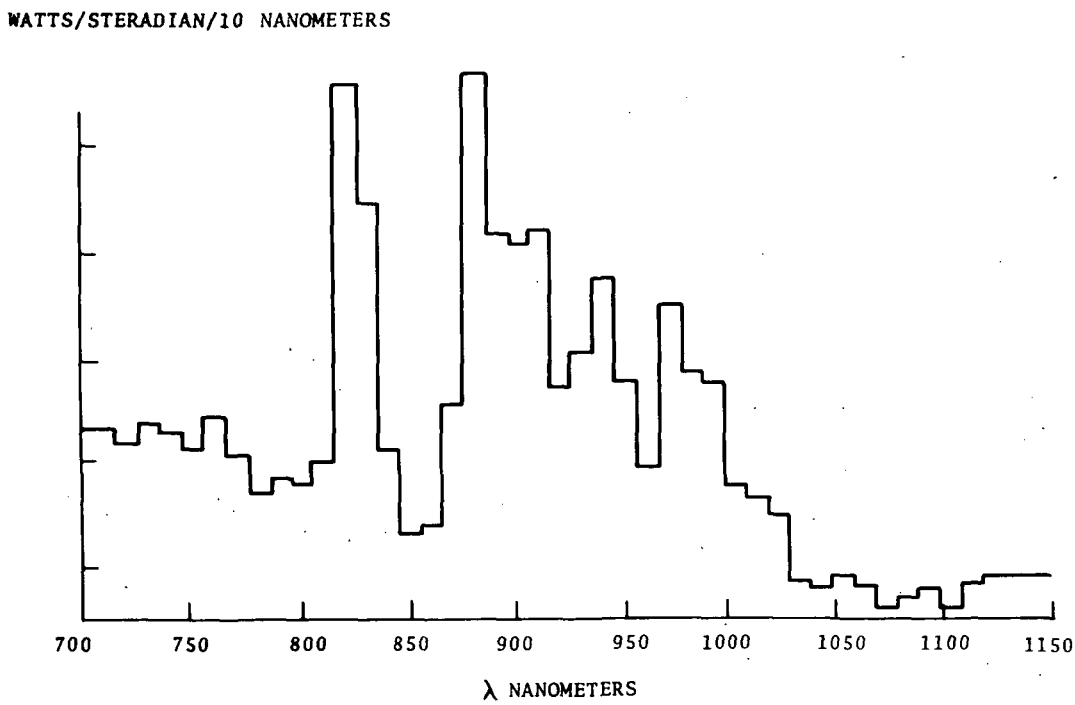


Figure 3. Spectral Distribution of Flash Energy

2.3 ATMOSPHERE

The signal radiated by the strobe is absorbed and scattered by the atmosphere. The effects of absorption and scattering are described in a study performed by AVCO[8] and scintillation and background effects are described in the Intermetrics report.[6]

2.4 PWI HARDWARE

The tests reported in this document were performed on three basically similar designs of an infrared-sensing PWI system. These are:

a. a system designed by the Fecker Division of Owens-Illinois, Inc. under the sponsorship of NASA/ERC,

b. a system developed by LORAL Corporation,

c. an improved LORAL system which incorporates a photodiode sensor in contrast to the photo conductive sensor in the earlier model.

Tests were performed on all systems, but due to various malfunctions in systems a and b as well as in the data recording system, the test results and analysis presented here relate only to the improved LORAL system.

2.4.1 Optics

The optics part of the flight test PWI system consisted of a ball lens, and an infrared filter. The ball lens is composed of two hemispheres between which is cemented the glass filter and a two-inch field stop. The effective aperture is thus 2 inches, despite the larger diameter of the ball lens.

The ball lens system (Figure 4) is mounted circumferentially

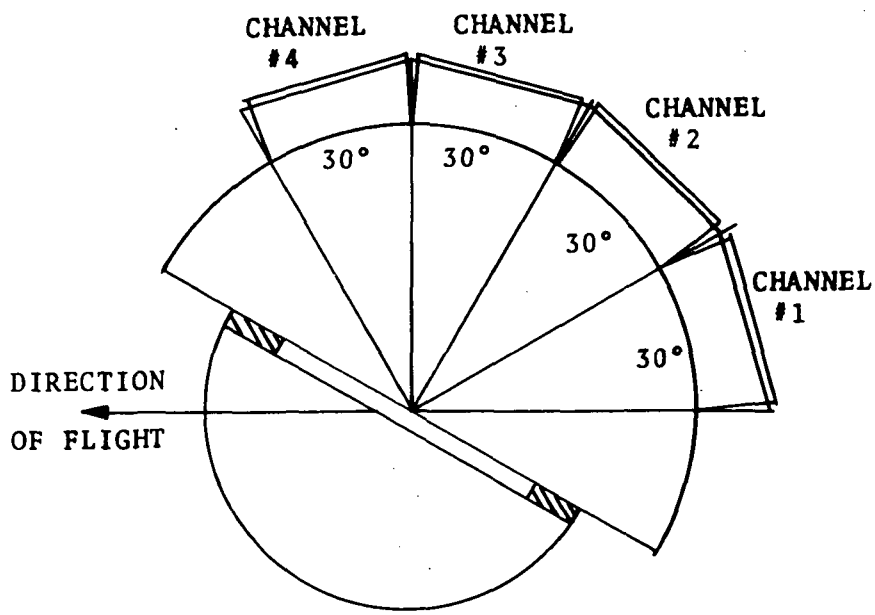


Figure 4. Ball Lens Azimuth

with optical axis pointing 60° away from the direction of flight (Figure 4).

The infrared filter used in the system is a Schott RG780 glass filter, 2-mm thick. The filter improves the system's signal to

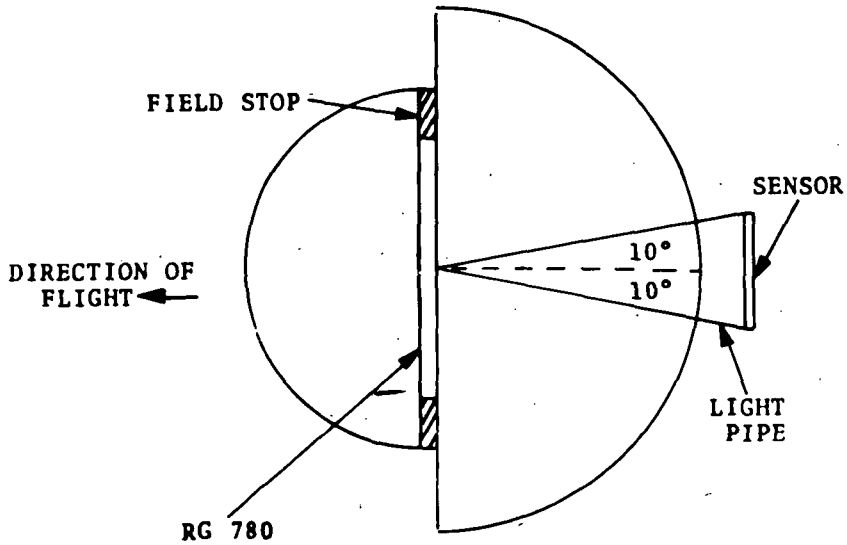


Figure 5. Ball Lens, Elevation

noise ratio, by limiting the background radiation while passing the IR content of the strobe signal[1].

Figure 6 depicts the effect of its transmission curve on the spectral responsivity of the silicon sensor.

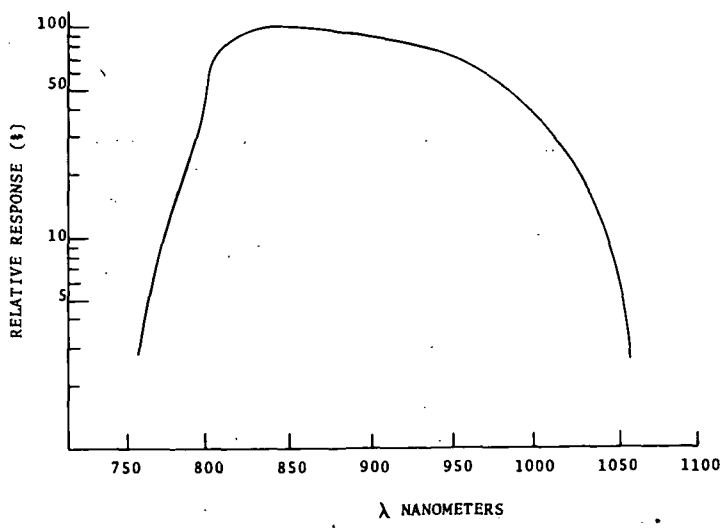


Figure 6. Spectral Sensitivity of Sensor as Modified by R.G. 780 Filter

2.4.2 The IR Sensor

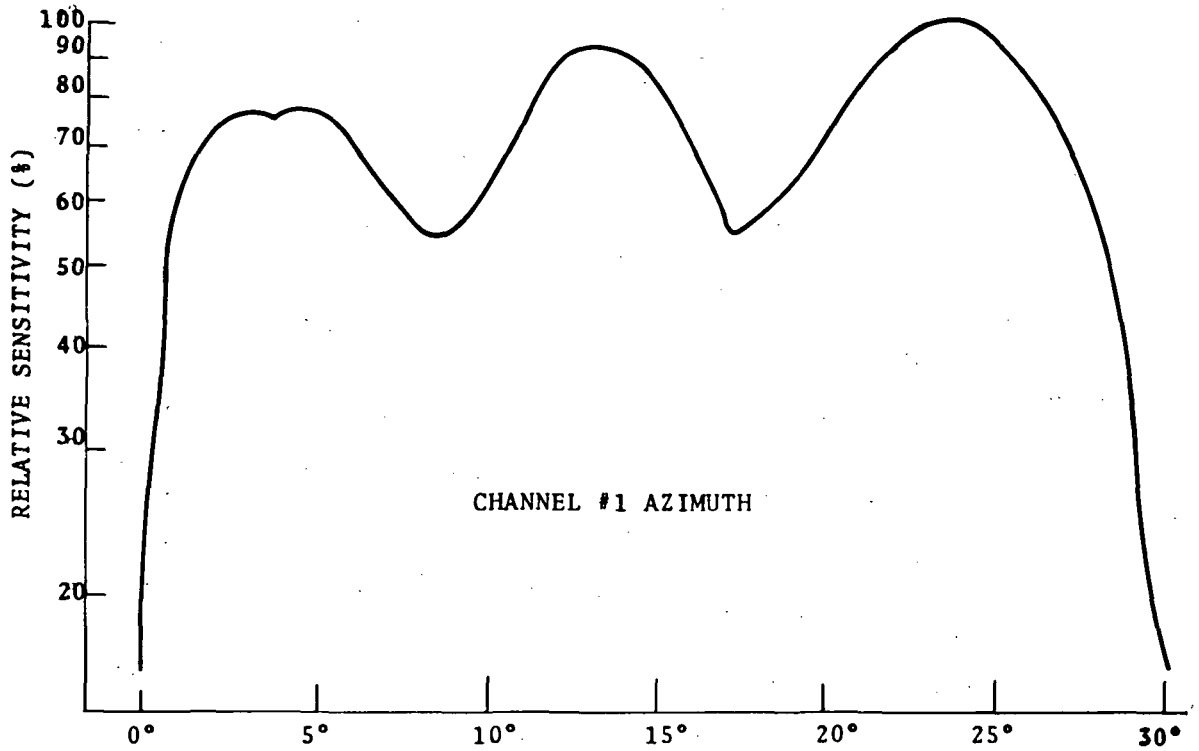
2.4.2.1 Optical Characteristics - The ball lens produces an image circle of a point light source such as an aircraft strobe at the aberrated focus on the diode surface. The apparent system sensitivity varies with changes in the source's relative angular position as a function of the image circle portion which illuminates the sensor. This produces a sensitivity pattern similar to the lobing pattern of an RF antenna both with regard to elevation and azimuth. Figure 7 depicts a typical pattern for one of the LORAL system channels[6].

The IR sensor consists of a PIN silicon photodiode, in a light pipe assembly. The geometry of the lens-sensor assembly determines each sensor channel's field of view. Each channel covers ±10° in elevation and 30° in azimuth. The total system is comprised of two detector heads of four channels each, covering ±120° in azimuth. The angular coverage of each channel is equal to 0.18 steradians, giving a total system coverage of 1.45 steradians.

2.4.2.2 Electrical Characteristics - The pertinent electrical parameters of the photodiode is its spectral responsivity? (Figure 6) which accounts for the device's ability to convert radiant power linearly into an equivalent current equal to 0.38 ampere per watt at a wavelength of 900 nanometers. The diode is employed as a current generator with a small reverse bias to sweep out carriers after a radiation pulse has been received. All other parameters such as dark current (leakage current) and diode acceptance are of secondary importance in this application.

2.4.3 Signal Processing

The signal change due to current variations in the photodiode is amplified by an operational amplifier that can be characterized by its transfer impedance, its bandwidth and center frequency. In the flight tests, the resulting voltage peak was recorded whenever a threshold level was exceeded. In the LORAL system, the threshold voltage varies in accordance with the peak noise voltages the system experiences during the 40 millisecond period immediately



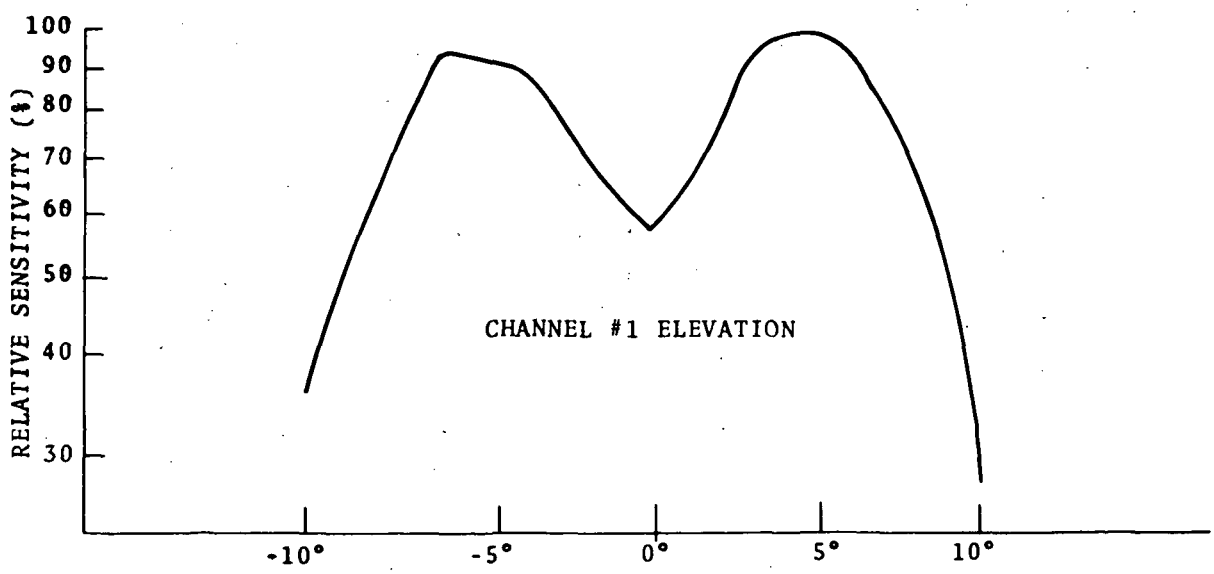


Figure 7. LORAL Detector Beam Pattern

preceding the signal pulse's arrival. When this pulse exceeds the threshold, the following occurs:

a. the trigger circuit drives the logic;

b. the data recording system is activated.

2.4.4 Logic

To effectively warn a pilot of another aircraft's presence, the logic circuitry is designed to provide discrimination against spurious signals. This discrimination is accomplished by requiring the occurrence of three consecutive signals before a warning is generated.

2.4.5 Display

Any PWI incorporates an output indicator whose function is to interface the detection circuitry with the pilot. Measurements on the relative merits and effectiveness of such displays were not within the scope of the tests reported here. It is expected that these display studies will be performed at least, in part, under the Visual Detection Simulation to be conducted at TSC.

3.0 OPTICAL IR PWI SYSTEM'S TEST PROGRAM SUMMARY

3.1 GENERAL

A series of tests were performed on the PWI hardware. These tests were divided into three phases:

a. laboratory tests;

b. static field tests;

c. flight tests.

3.2 LABORATORY TESTS

Laboratory tests were performed on the photodiode LORAL PWI. Measurements were made on this system to:

a. determine the detector sensitivity profile;

b. verify the gain and frequency response data provided by the designers;

c. correlate the system noise characteristics with design information provided.

3.3 FIELD TESTS

The field tests were conducted at the FAA National Aviation Facilities Experimental Center (NAFEC). These tests were intended to extend the laboratory tests to include atmospheric and background effects. The field tests' purpose was to:

a. check out equipment prior to flight testing

b. exercise the data processing programs;

c. determine if the sensitivity lobe patterns were affected by varying background conditions;

d. familiarize NAFEC personnel with the equipment.

These results were accomplished and, as reported in Ref. 6, the capability to evaluate data immediately following a flight test was not achieved.

3.4 FLIGHT TESTS

The flight tests were performed at the FAA/NAFEC facility during June and July, 1971. NAFEC provided equipment and personnel support. These tests were designed to expand the results obtained from the laboratory and field tests by introducing the environmental effects encountered in flight.

The tests' objectives were to:

a. Determine the optical IR PWI system's performance characteristics under the influence of atmospheric conditions, shock effects, vibration and electromagnetic interference. Specifically, this determined the cumulative probability of detection which would have existed for two aircraft on a collision course.

b. Apply a general analytic model, so these test results would be extended to include effects different from those encountered during the flight tests.

The flight aircraft were flown on parallel courses during these flight tests so sufficient data could be obtained.

4.0 FLIGHT TEST DESCRIPTION

4.1 GENERAL

For the flight tests, the PWI Hardware was mounted aboard a Convair 240 and the strobe (Whelen Model HD Beacon) was mounted below the fuselage of a Grumman "Gulfstream" (Figures 8 and 9). Both aircraft were equipped with the data recording systems described below. Transducers were installed on both aircraft to provide pitch and roll indications (attidute data) to the recording equipment and the aircraft heading indicator was also modified for automatic data recording.

The two aircraft were flown in formation at selected constant relative bearings and ranges to obtain a sufficient number of data points in the sensitive center region of each channel. All flights were performed with a differential altitude between the aircraft of 150 feet to minimize the possibility of collision. The varying parameters for the flights were:

Altitude	500 to 10,000 ft.
Range	.5 to 1.5 nautical miles
Headings	Approximately 60°, 150°, 240° and 330°

4.1.1 Flight Summary

During the period from June 10 to July 27, a total of 24 flights were performed. All flights were conducted over water near Atlantic City, New Jersey, where the aircraft could operate without hazard to general traffic. All flights were flown in a rough quadrangle with principal headings as shown above to include a variety of sun angles. Each leg of the flight lasted for about 6 minutes permitting some 300 data points. Each leg constituted a *run*.

One hundred thirty-eight of a total of 286 runs were performed with the improved LORAL system described in Section 2. The analysis of the data obtained on these flights is presented in Section 5. The Fecker system exhibited such extreme sensitivity to background radiation and spurious signals that useful results could not be obtained.

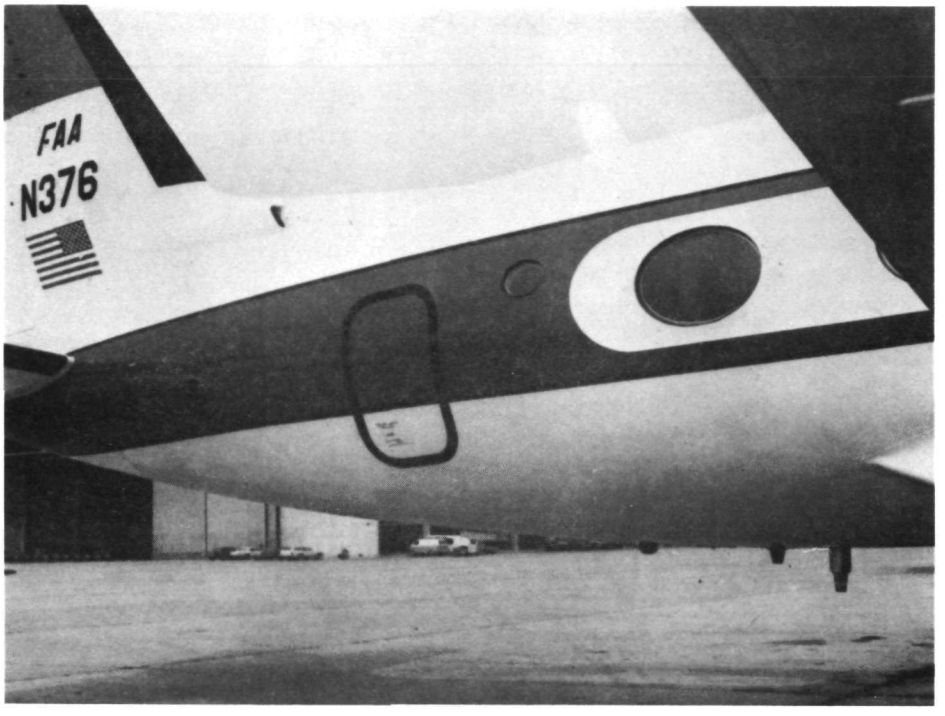


Figure 8. Strobe Equipped Aircraft

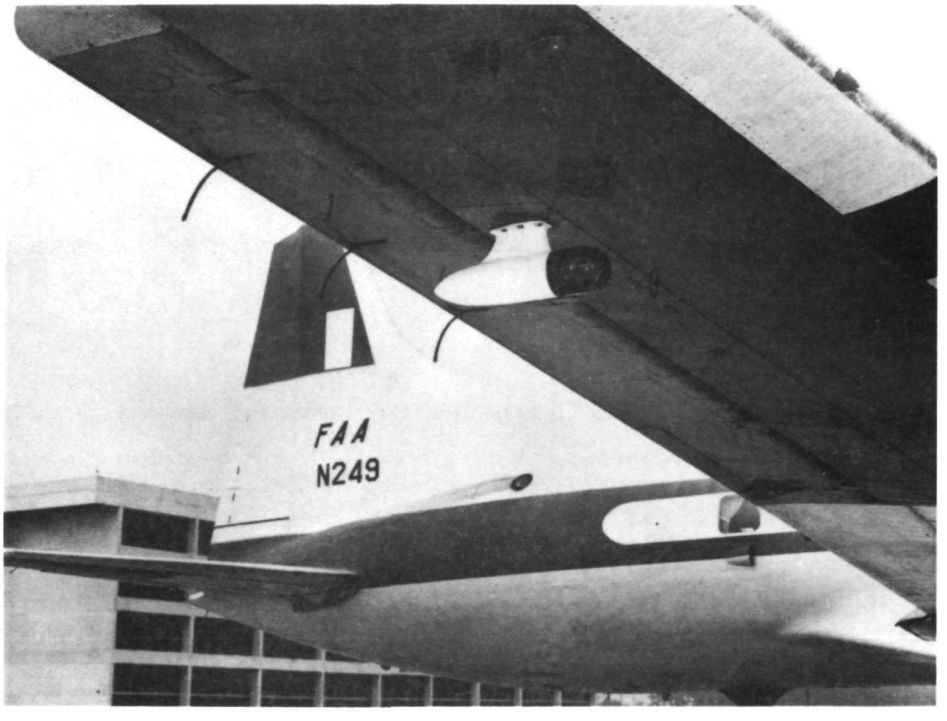


Figure 9. PWI Equipped Aircraft

However, adequate data was obtained from the improved LORAL system. The data obtained from the earlier runs of the original LORAL system were not analyzed.

4.2 THE DATA ACQUISITION SYSTEM (DAS)

Two data acquisition systems, one aboard each aircraft, were used in the flight tests. The data recorded in the strobe A/C were:

a. Strobe signal event time

b. Strobe signal event pulse

c. A/C pitch

d. A/C roll

e. A/C heading

The data recorded by the PWI DAS were:

a. PWI signal event time

b. PWI signal peak amplitude

c. PWI signal event pulse

d. Channel identification

e. A/C pitch

f. A/C roll

g. A/C heading

h. Bearing Validation

i. Nominal Range (Manual switch setting)

Difficulties were encountered in recording strobe signal pulse amplitude, outside air temperature, and sky background radiation level.

Additional test data were manually recorded for each run by the test engineer. These were:

a. identification of the PWI channel under test

b. test number

c. air temperature

d. test duration

e. range (norminal value only)

f. barometric pressure

g. heading

h. altitude

i. visibility

j. cloud cover

k. dew point

4.2.1 Data Recording

Figure 10 shows the PWI data recording apparatus used in the flight tests. The test data were recorded on a digital recorder manufactured by Incre-Data Corporation of Albuquerque, New Mexico. The system contains:

a. a crystal-controlled clock;

b. an analog-to-digital converter and multiplexer and

c. a number of digital input channels controlled by manually operated switches;

d. tape advance and record circuitry.

The PWI system under test produced a pulse whose amplitude was proportional to the peak signal power received. When this signal exceeded a threshold in the discriminator, a second pulse of fixed weight was generated indicating a detection "*event*". The original signal pulse was fed into a track and hold amplifier or peak detector within the data acquisition system. The output of the amplifier was a fixed dc level equal to the pulse's peak voltage. The "event" pulse was fed into the data acquisition system, where it initiated the recording process, sequentially interrogated the clock, the A/D converter and the digital channels. At the end of the recording cycle, the system was reset to await the arrival of the next pulse. The output of the peak detector was fed to

the A/D converter where it was held until interrogated by the multiplexer.

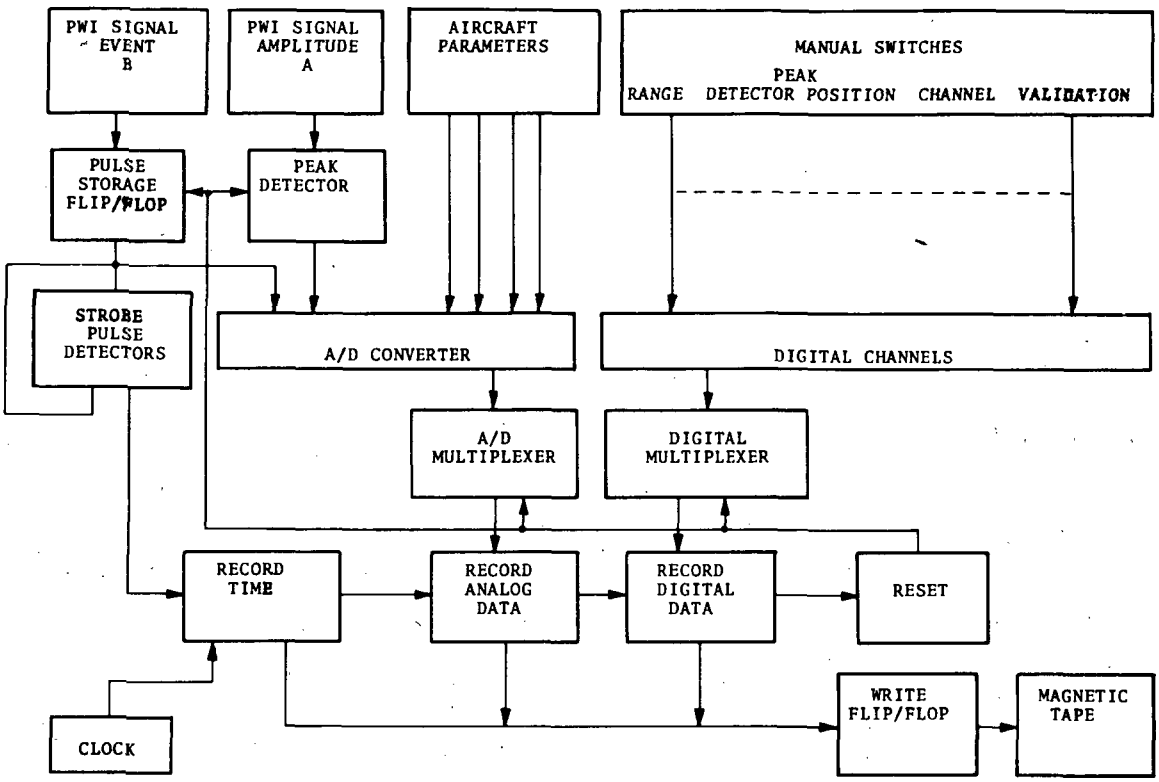


Figure 10. PWI Data Acquisition System

4.3 TEST PROCEDURE

Prior to each flight, the strobe DAS and PWI DAS were activated and the strobe lamp operated for a short sequence of flashes. The recorded events obtained provided a means of synchronizing the clocks in the two data acquisition systems.

After rendezvous at the test area, the altimeters were adjusted and an altitude for the test runs was selected which minimized clouds obstructing the strobe signal. The cockpit of the PWI aircraft was fitted with a sighting device which permitted the pilot to keep the target aircraft at a relatively constant bearing with an estimated tolerance of ±3° azimuth and elevation. When the pilot had determined that the target aircraft was at the device

"bearing", he operated a pushbutton switch which produced an audio signal for the test engineer and a digital signal recorded by the Data Acquisition System. This provided the bearing validation indicated in Figure 10.

5.0 DATA ANALYSIS

5.1 GENERAL APPROACH

Figure 11 shows the steps taken in the analysis effort.

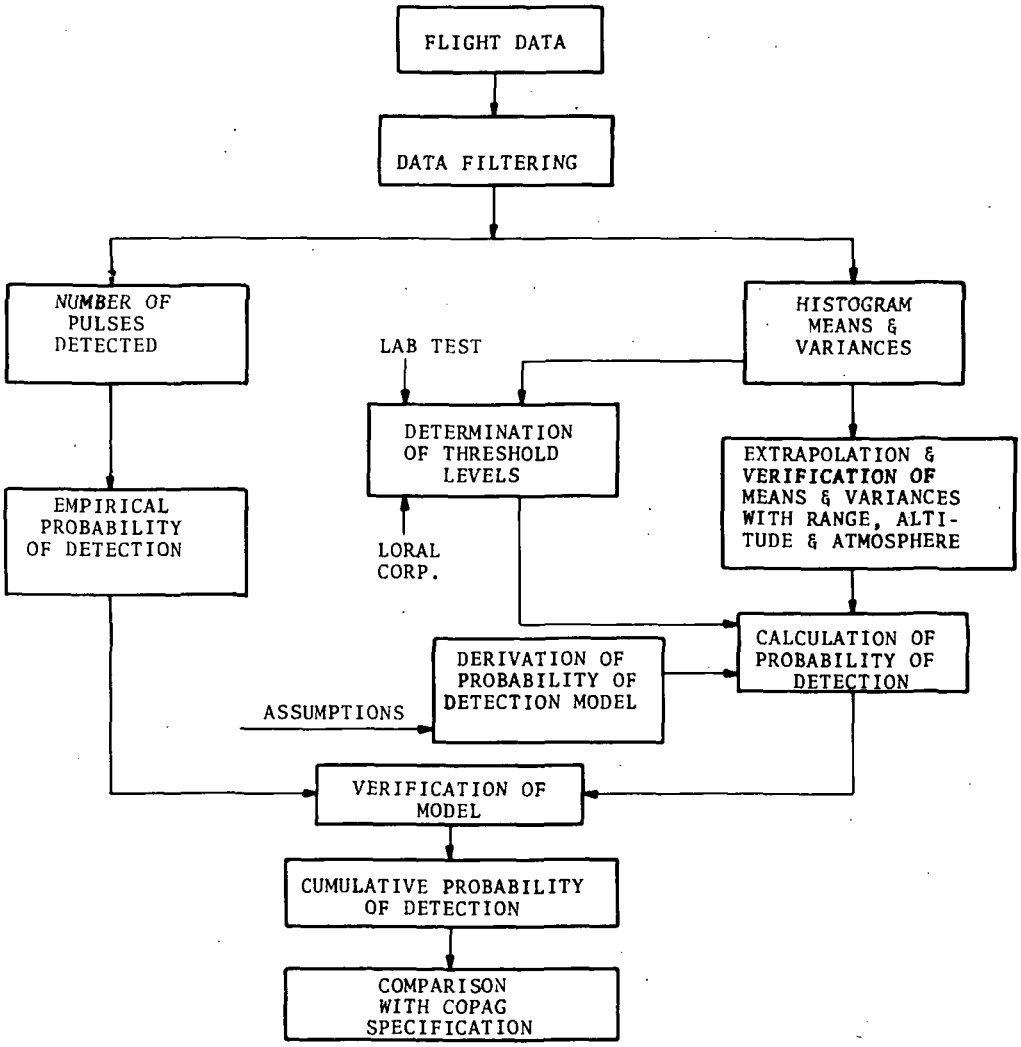


Figure 11. Data Analysis Flow Chart

The raw flight test data were subjected to a calibration adjustment and invalid data eliminated. The resulting data points were then used to obtain:

a. Histograms, mean and variance of the peak signal levels for various ranges;

b. number of missed detections;

c. empirical determination of the probability of detection as a function of range.

The mean values of the peak signal levels were generally consistent with an atmospheric model which considers temperature, range, humidity, visibility and altitude. The ratio of the variance divided by the mean signal level was proven empirically to be range independent for the conditions encountered. This range independence of normalized variance was used in conjunction with the predicted change in mean level to obtain the variance used for detection probability which is based on a series of assumptions concerning the fluctuation in signal levels measured during the flight tests. The mean and variance determined from the measurements in conjunction with threshold levels are used in the model to determine the resulting probability of detection for a single pulse. The validity of the assumed model was determined by comparing the probability of detection curves it generated with the probability of detection deduced from the number of times the signal exceeded the threshold of the PWI device. Reasonable agreement is shown for the ranges at which direct measurements have been made. No firm conclusion regarding the validity of the model for ranges larger than 1.5 nmi can be reached. The resulting model for probability of detection which represents the conditions encountered during the flight tests are used to calculate cumulative probability of detection and this result is compared with the specifications developed by the COPAG committee.

5.2 FILTERING OF DATA

The first task undertaken during this analysis phase was to combine, correlate and examine the data recorded during the flight on three separate tapes as a function of time. The data acquisition system on the two aircraft each yielded a tape with the data listed in 4.2, including the peak amplitude from the PWI DAS, time of occurrance and relative amplitude of the flash from the strobe

DAS. Range information from the ASMS system aboard the PWI aircraft was combined with the other two tapes by plotting resultant time histories, that is, peak amplitude and range versus time.

A careful examination of the records showed that a portion of the data failed to show the expected inverse square law dependance of the peak signal values on range. Subsequent investigation proved that the peak detectors used during these runs malfunctioned, causing the recorded signal to remain relatively constant even though the input signal levels changed by a significant amount. Data which exhibited this behavior was not used further in the course of the data reduction.

5.3 DATA REDUCTION

5.3.1 Number of Pulses Detected

The signal events were examined to ascertain the number of times the signal exceeded the threshold established within the PWI device. The number of these pulses detected (N_d), divided by the number of strobe pulses emitted during a run (N), yielded the empirical probability of detecting a single pulse (P_d) for each range increment. These parameters are shown in Tables 1 and 2.

5.3.2 Number of False Detections

The number of pulses detected that could not be correlated to a strobe pulse event constituted a measure of the number of false detections occuring during a run, as shown in Tables 1 and 2.

5.3.3 Histograms, Mean and Variance of the Received Signal

Data from each flight at a specified altitude was grouped by runs at indicated headings and subsequently sorted by computer according to selected range increments. The peak signal levels were recorded from threshold to 800 mv in 50-mv intervals. The ranges were recorded from 4,000 ft to 10,000 ft. and were sorted in 500-ft intervals.

Histograms of the peak signal levels were then generated by determining the number of times the peak amplitude fell within the 50-mv intervals for the given range cell of 500-ft width. The

TABLE 1. FLIGHT NO. 180-1, 9500 FT. ALTITUDE CHANNEL

RANGE	HDG	N	N_d	P_d	m_m	σ_o	σ_o/m_m
5000	152	151	133	.88	.714	.075	.104
5500	152	178	168	.94	.561	.14	.25
5500	157	12	12		.625	.076	.122
6000		54	52	.94	.515	.119	.232
6000	242	54	50	.93	.490	.148	.302
6500	157	51	44	.86	.436	.103	.236
6500	242	33	30	.91	.384	.123	.317
6500	330	92	90	.98	.456	.137	.3
6500	060	6	6		.469	.111	.236
7000	157	128	100	.78	.344	.089	.258
7000	242	75	58	.77	.334	.093	.278
7000	330	286	242	.85	.338	.098	.288
7000	060	172	142	.83	.424	.098	.230
7500	157	116	96	.83	.349	.088	.253
7500	242	268	242	.90	.333	.074	.220
7500	330	308	268	.85	.330	.087	.263
7500	060	120	104	.88	.356	.090	.252
8000	157	12	10	.83	.342	.077	.226
8000	060	48	29	.61	.303	.087	.288
8500	157	48	22	.47	.322	.059	.183
8500	060	26	17	.65	.286	.057	.198
9000	157	62	24	.38	.279	.057	.200

REMARKS

The data in this table were obtained in five runs, as follows

Run 1 HDG 152 N 329 F = 2
Run 5 HDG 157 N 483 F = 2
Run 6 HDG 242 N 430 F = 0
Run 7 HDG 330 N 686 F = 9
Run 8 HDG 060 N 372 F = 5

Range = in Feet
Heading = Magnetic course, direction of flight

N = Number of Pulses Emitted

N_d = Number of pulses Detected

P_d = Empirical Probability of Detection (Nd/N)

m_m = Measured Mean

σ_o = Measured Standard Deviation

σ_o/m_m = Normalized Standard Deviation

F = Number of Noise Pulses Exceeding threshold during Run

TABLE 2. FLIGHT NO. 207-1 500 FT. ALTITUDE CHANNEL 1

RANGE	HDG	N	N_d	P_d	m_m	σ_o	σ_o/m_m
4500	054	22	17	.77	.579	.095	.163
4500	232	42	40	.95	.489	.167	.34
5000	054	76	73	.96	.525	.142	.270
5000	232	250	232	.93	.586	.133	.22
5500	054	59	59		.426	.081	.19
5500	232	40	38	.95	.345	.134	.38
6000	052	44	33	.75	.261	.094	.358
6000	249	323	195	.91	.276	.089	.321
6000	054	19	19		.331	.080	.241
6500	052	88	82	.93	.243	.093	.381
6500	249	29	21	.73	.199	.087	.410
6500	054	32	22	.69	.219	.052	.238
7000	232	133	91	.68	.194	.084	.433
7000	054	17	16	.41	.169	.102	.6
7500	059	176	141	.8	.198	.083	.417
7500	232	197	145	.74	.189	.080	.422
7500	054	12	11	.92	.202	.062	.3
8000	059	25	20	.8	.147	.055	.37

REMARKS

Data in this table were obtained in six runs, as follows:

Run 1 HDG 052 N 132 F = 0
Run 2 HDG 249 N 362 F = 1
Run 3 HDG 059 N 201 F = 1
Run 4 HDG 232 N 232 F = 0
Run 5 HDG 054 N 237 F = 1
Run 6 HDG 232 N 332 F = 0

N = Number of pulses emitted

N = Number of pulses detected

P_d = Empirical Probability of Detection $\frac{N_d}{N}$

m_m = Measured Mean

σ_o = Measured standard deviation

$\sigma/_o m/_m$ = Normalized Standard Deviation

F = Number of Noise pulses Exceeding threshold during Run

number of events in each interval was divided by the number of total events establishing the relative frequency of occurrence within each interval. The resulting values were plotted against the voltage levels to present the functional form of the histogram. A sample histogram is shown in Figure 12.

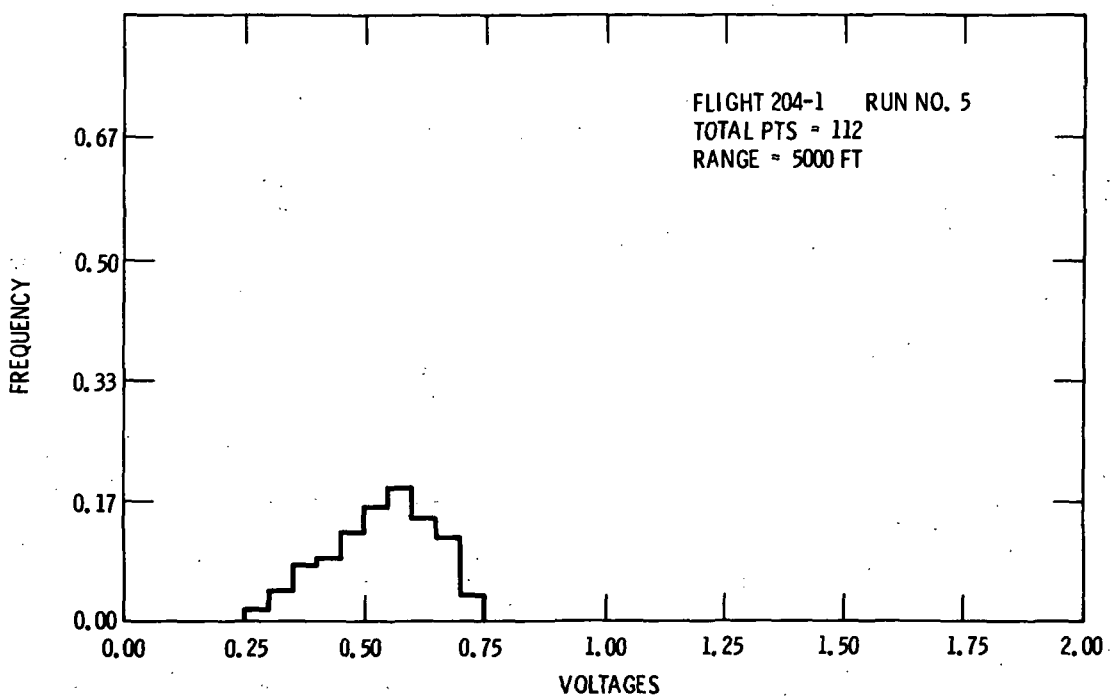


Figure 12. Typical Histogram

Additionally, for each of these range sorted data groups, a mean value and a variance were calculated for each of the range cells. These values for the mean and variance are shown in Tables 1 and 2.

5.4 DETERMINATION OF THRESHOLD LEVELS

This threshold level is necessary to predict the probability of detection for the PWI device.

The variable threshold level with which the PWI device operated during the flight test was not recorded during these tests. Some information about the minimum levels of these thresholds,

particularly for the tests conducted at the 500-ft altitude level, were concluded from the histograms. These indicated that a threshold level on the order of 100 mv occurred during these tests. Since the minimum threshold for the PWI device is 100 mv, this value was selected for the minimum threshold encountered for the 500-ft altitude tests.

A series of subsequent laboratory tests conducted at TSC and flight tests conducted independently by Loral Corporation indicated a nominal threshold level of 200 mv due to background and system noise for blue sky conditions. Subsequent investigations of the histogram data tended to confirm this value as the minimum obtained during the 9500 ft altitude tests. Because of the possibility of reflections from clouds causing an increase in the background light level during all tests, a maximum value for the threshold of 300 mv was selected as reasonable.

5.5 ANALYSIS OF MEAN AND VARIANCE

The mean and variance of the received signal and noise is required for the determination of the probability of detection. The mean peak signal received can be expressed as follows:

$$\overline{V}_s = k\ T_a(r,T,H,V_r)$$

$\overline{V}_s$ is the mean value of the peak signal.

k is a system constant combining strobe signal strength, detector sensitivity and PWI transfer impedances.

T_a is the atmospheric transmission as a function of range (r), temperature (T), relative humidity (H), visibility (V_r) and altitude (h). $1/r^2$ is the free space attenuation. T_a can be evaluated for any specific set of r, T, H, V_r using a computer program developed in "PWI Atmospheric Transmission Study" (Ref. 7).

A value of k was obtained using this expression which corresponds to the mean level recorded at the 9500 ft altitude for the visibility, temperature range, humidity and altitude encountered. This value of system performance k was then used in conjunction with the atmospheric conditions, altitude and range prevailing in other test

runs to predict the new mean levels. The predictions agree reasonably well with the resulting mean levels determined from the data. Comparison of the analysis to the data recorded revealed a close correlation for flights at 3500 ft and 500 ft. Agreement was within 50% for mean values measured at 1000 and 7500 ft altitude. Figures 13 and 14 show the model values indicated by the lines and the data points indicating measured mean levels for 500 ft and 9500 ft.

The variance values used in the probability of detection model are based on the observation that the standard deviation of the signal varied with range in roughly the same fashion as the mean. The normalized standard deviation (σ/m) shown in Tables 1 and 2 is assumed independent of range. This is ascribed to the aircraft induced random movement of the detector pattern during flight. The data in Figure 15 shows the values of the σ/m quotient to lie generally between .2 and .4 and these numbers were, therefore, adopted as boundary values for the detection model.

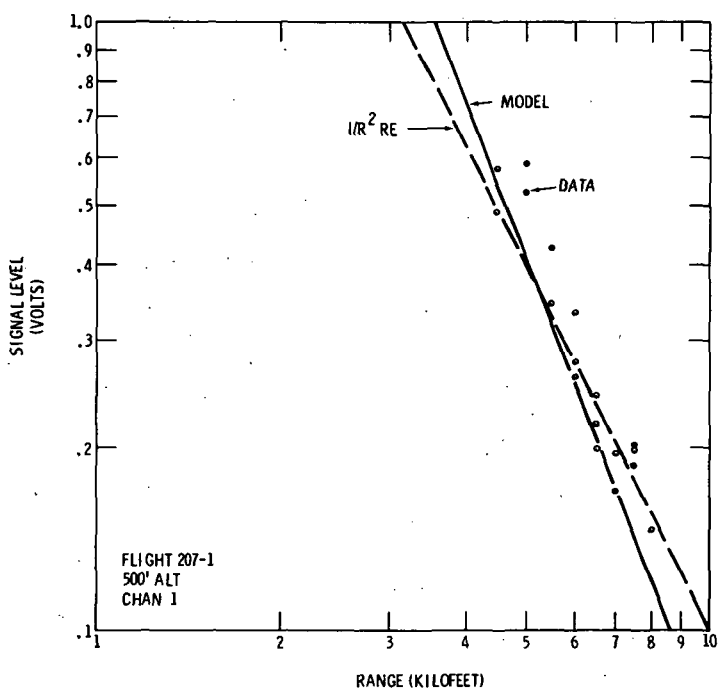


Figure 13. Mean Peak Signal Level Vs Range (500' Altitude)

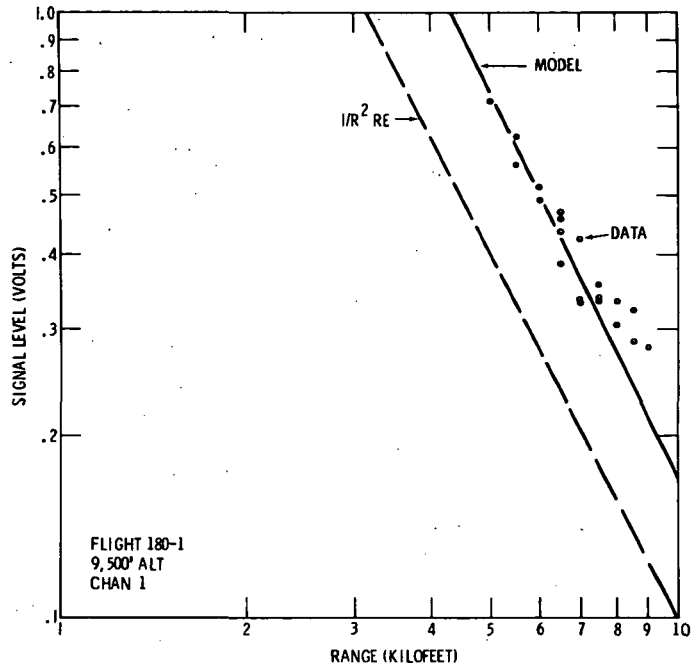


Figure 14. Mean Peak Signal Level Vs Range (9500' Altitude)

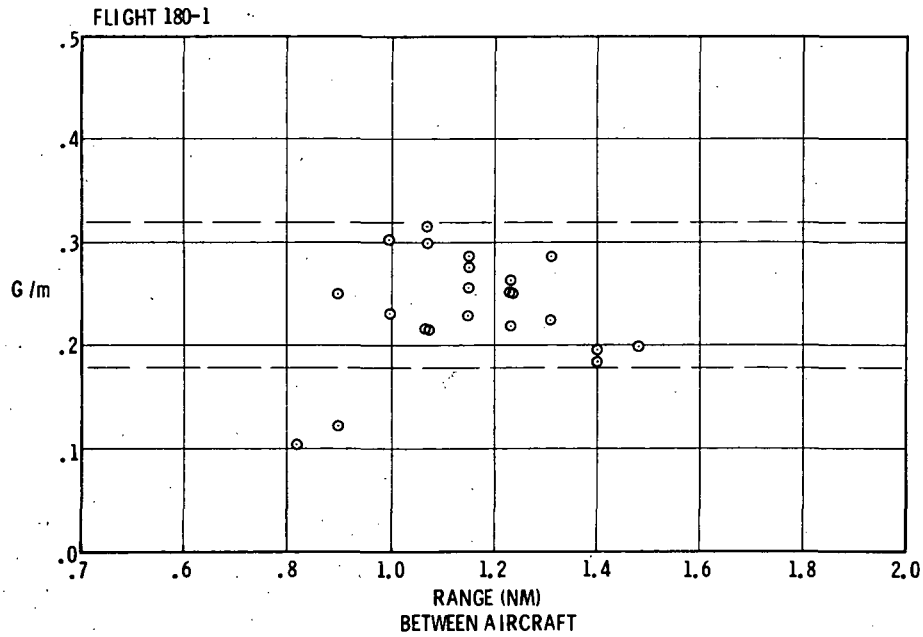


Figure 15. Normalized Standard Deviation Vs Range

5.6 DETERMINATION OF PROBABILITY OF DETECTION MODEL

The peak signal voltage appearing at the threshold within the PWI tested may be expressed as:

$$V_s = \frac{K_o \; T_a \; \mu(\theta_1)\mu(\theta_2)\omega(\phi_1)\omega(\phi_2)}{r^2} \qquad \text{where:}$$

- r is the range between the signal source and the detector.
- T_a is the atmospheric transmission factor;
- μ is the relative power distribution of the strobe light in the θ_1 and θ_2 directions of the PWI;
- ω is the detection pattern of the sensors in the ϕ_1, and ϕ_2 directions of the strobe;
- K_o includes the peak output of the strobe light (a random variable) and the sensitivity and the transfer impedance of the PWI device.

All these factors except r and T_a are random variables. This expression may be written as a summation of terms by taking a logarithm of both sides of the equation. If the central limit theorem is assumed to hold for this sum of random variables, the resulting probability density function (pdf) for V_s is lognormal.

$$p(V_s) = \frac{1}{\sqrt{2\pi}\; V_s \cdot \sigma_o} \exp\left(-\frac{1}{2}\left(\frac{\ln V_s - m_o}{\sigma_o}\right)^2\right)$$

where m_o and σ_o are two constants related to the mean and variance of the distribution. This distribution also describes the combined effect of signal and noise as long as the signal fluctuations are much greater than the variations attributed to noise, and the mean signal level is much larger than the r.m.s. value of the noise voltage. Comparison of the functional forms of the pdf and the histograms do not show very close agreement. The lack of agreement may be attributed to the scarcity of points available in individual histograms, as well as to the effect of the threshold excluding lower values of signal within the distribution. No attempt was made to combine histogram data.

The probability of a single signal pulse exceeding the threshold is

$$P_D = \int_{V_t}^{\infty} p(V_s)dV_s$$

where V_t is the threshold voltage, $p(V_s)$ is the probability density function of signal distribution. The probability of detection was numerically calculated for the values of threshold voltage V_t encountered, the mean peak signal level m_{om}, and signal variance σ_o. Figures 16 and 17 show the measured probabilities of detecting a single pulse versus range at two altitudes together with the probability curves determined from the model. The empirical values agree quite well with the model results; the analytic curves bound the measured data. The curves are plotted for two threshold levels. The minimum threshold level determined from the histograms was 100 mv for the 500 ft altitude case and 200 mv for 9500 ft altitude case. The maximum threshold for both altitude cases was 300 mv.

For both runs, it was found that measured normalized standard deviation (σ_o/m_m) varied between .2 and .4 and this was used to plot two separate curves for each threshold level. The model for atmospheric attenuation developed by AVCO predicts an essentially linear decrease of signal attenuation with increasing altitude and this was confirmed by the tests. The probability of detection curves (Figure 16) for 500 ft altitude are an example of this slightly reduced range at lower altitudes.

5.7 CUMULATIVE PROBABILITY OF DETECTION

The cumulative probability of detection C_N is defined as the probability of a PWI having generated at least one warning of an intruder aircraft at or prior to the time at which the separation between the two aircraft has decreased to a range (r).

The COPAG PWI characteristics specify that a PWI shall have a cumulative probability of detection of .95 at a range of one nmi and of .05 at a range of 3 nmi.

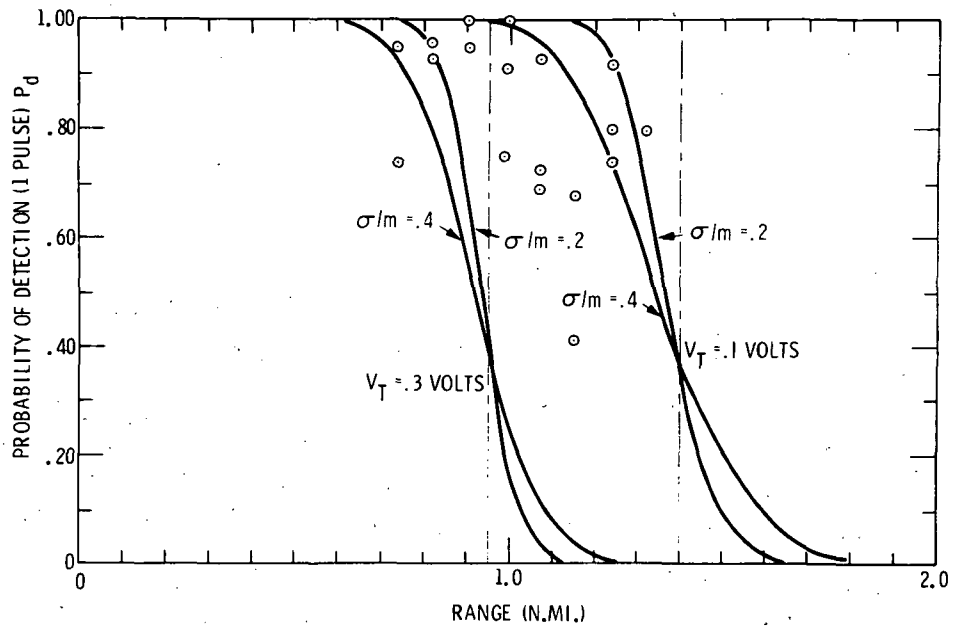


Figure 16. Probability of Detection, (Single Pulse) Vs Range Flight 207-1 Altitude 500 Feet

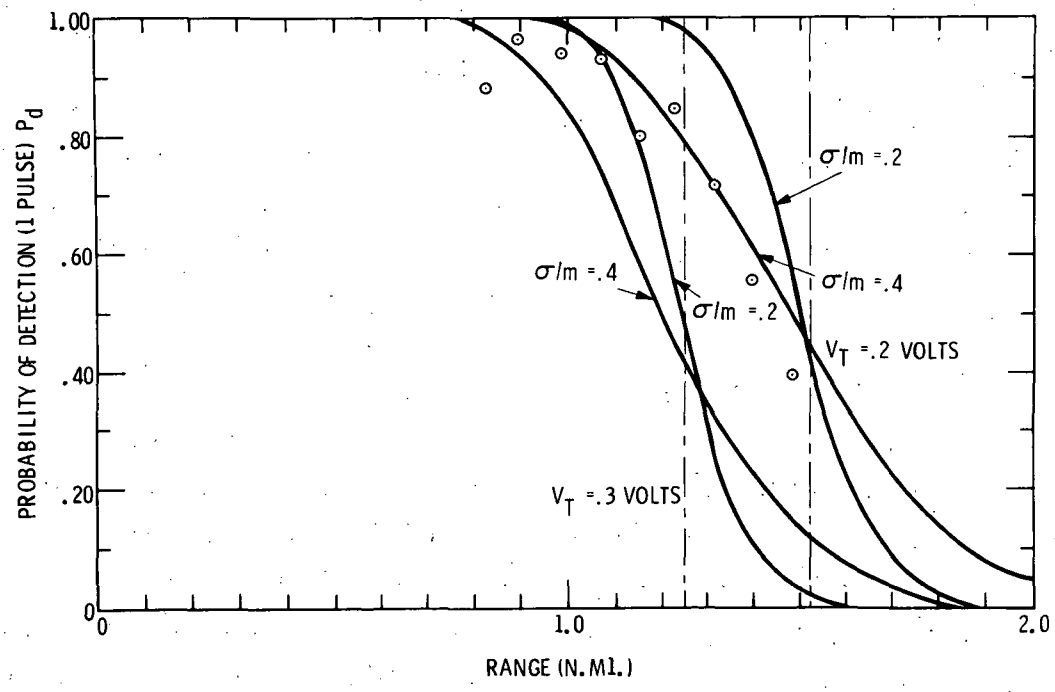


Figure 17. Probability of Detection, (Single Pulse) Vs Range Flight 180-1 Altitude 9,500 Feet

The PWI tested requires reception of three successive pulses to generate an alarm. To compare system performance with the COPAG specs, it is, therefore, necessary to determine the cumulative probability of three successive pulses exceeding the threshold at various ranges. This can be computed from the values given above for the probability of detection of a single pulse and using the expression derived from Reference 9:

$$C_N = (1-Q_N)C_{N-1}+Q_N(1-Q_{N-1})C_{N-2}+Q_NQ_{N-1}(1-Q_{N-2})C_{N-3}$$
$$+Q_NQ_{N-1}Q_{N-2}$$

Figures 18 and 19 for two altitudes of interest.

5.8 COMPARISON OF C_N WITH THE COPAC SPECIFICATION

Table 3 compares the values of cumulative probability of detection for the two test flights with the COPAG Specification.

TABLE 3. COMPARISON OF CUMULATIVE PROBABILITY OF DETECTION

CUMULATIVE PROBABILITY OF DETECTION	COPAG SPECIFICATION (NMI)	FLIGHT TEST RESULTS (NMI)			
		500 FT ALTITUDE		9500 FT ALTITUDE	
		LOWER BOUND	UPPER BOUND	LOWER BOUND	UPPER BOUND
>.95	1	.5	1.0	.7	1.1
<.05	3	.85	1.3	1.2	1.45

5.9 ANALYSIS SUMMARY

The comparison between the measured data and the bounds provided by the analytic model for the probability of detecting a single pulse shows good agreement. The assumptions used in obtaining the analytic model must be reviewed to detail their effect on the cumulative probability of detection which is determined from the best and worst case bounds.

5.9.1 Log Normal Distribution

The log normal distribution has been assumed as an adequate description of the flight test signal amplitude measurements. The major cause of this signal fluctuation is due to changes in orientation of the detector and strobe patterns due to relative motion

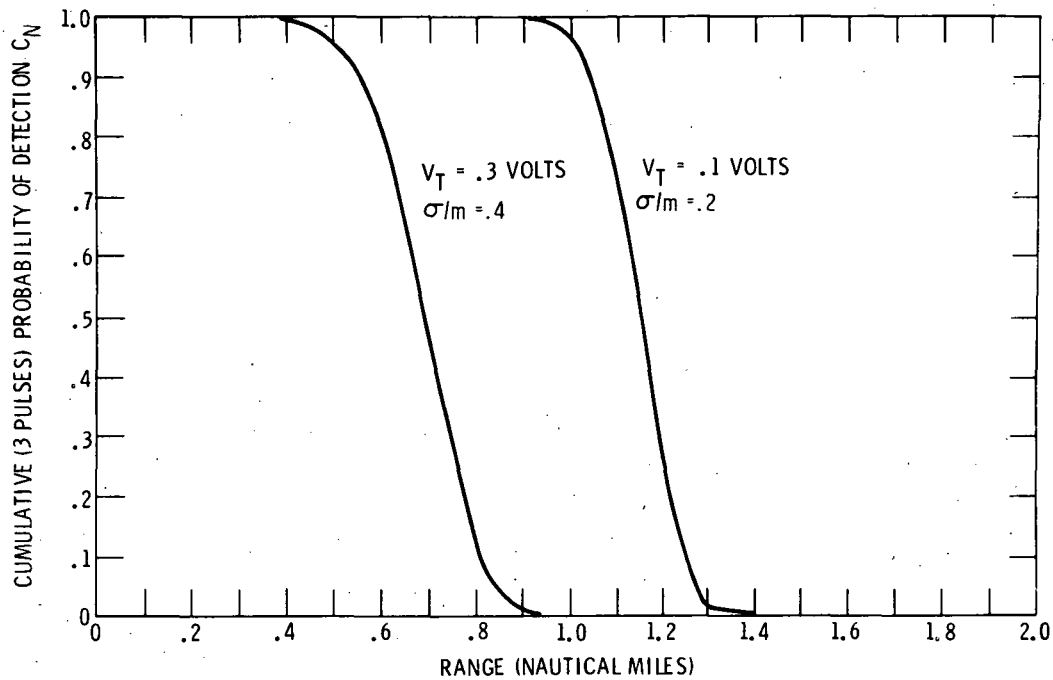


Figure 18. Cumulative Probablility of Detection (Three Pulses) Vs Range Flight 207-1 Altitude 500 Feet

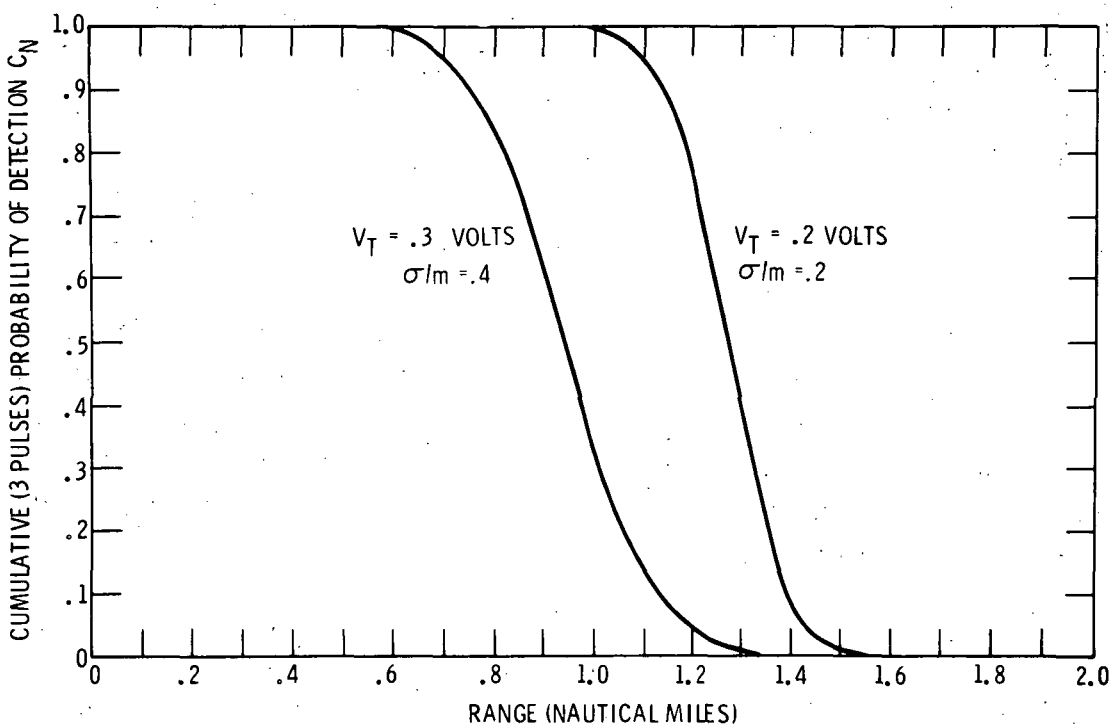


Figure 19. Cumulative Probability of Detection (Three Pulses) Vs Range Flight 180-1 Altitude 9,500 Feet

between the aircraft. It is possible that some other distribution would have bounded the measured data. Indeed at large ranges, where the signal to noise ratio is low, the resultant distribution of signal and noise will not behave as a log normal distribution, but as some other distribution which includes fluctuation due to noise. Over the limited range used in these tests however, the recorded data ia described by a log normal distribution.

The cumulative probability of detection curves closely resemble the shape of the probability of detection curves from which they are generated. Values of cumulative probability of detection occur at somewhat shorter ranges than similar values of detection for the probability of a single pulse.

At values of probability larger than .4 this decrease in range is approximately equal to 0.2 nmi a value resulting from the closing speed and the time between samples required for three consecutive samples. This range translation effect causes the cumulative probability of detection to be described quite accurately in the regions where the probability of detection has been verified with empirical data. This region extends from probability values of .4 to 1.0. Low values for the cumulative probability of detection are sensitive to the assumptions regarding the tail shape of the distribution selected and should be regarded as an estimate of what the performance bounds would have been.

5.9.2 Dependence of Mean and Variance with Range

Over the range between aircraft for which these measurements were made, the signal exceeded the noise level by a significant margin. It was noted that the recorded variance and mean signal amplitude values changed in the same fashion with range. This dependence was used to calculate the variance as a function of range. At low signal to noise ratio values which would have occurred at ranges beyond 1.5 nmi, the major cause of received signal fluctuation would have been due to noise, causing the functional dependence for variance to change. There the assumed range dependence for variance causes the tail of detection probability

bounds to be in error at large ranges but not at shorter ranges where the value of the probability curves exceed .4.

5.9.3 Determination of Threshold Level

As may be noted from the results, the threshold level has a significant effect on system performance with range. The threshold levels chosen, appear reasonable based on the agreement between the measured data and the bounds provided by the model.

5.9.4 Independence of Detection Samples

The expression for cumulative probability of detection assumes that the pulses received are independent. This assumption was not proven but is strongly suggested by the long interval between samples (1 sec), and the agreement between the analytic model and the data.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 GENERAL

The flight test and analysis of the optical IR PWI system were conducted to obtain information useful for developing a general system model that would permit performance predictions over a broad range of operational conditions. While analyzing the data obtained from the flight tests, it became apparent that insufficient information was available to completely describe a general model for predicting system performance. However, the information obtained was adequate to characterize the mean peak signal levels obtained as a function of range, altitude and atmospheric conditions. On this basis, a limited model was developed that characterizes the performance of the specific system tested in terms of the probability of detecting a single pulse versus range. Empirical data showed that this limited model bounded the experimental data for the conditions encountered during the tests. As a result, it was possible to predict the resulting cumulative probability of detection and to compare this with the specifications prepared by the COPAG committee.

The cumulative probability of detection describes the liklihood of a detection occurring on board a PWI protected aircraft which is flying on a collision course with a second aircraft.

In conclusion, the optical IR PWI system tested met the COPAG performance specifications for a detection likelihood of 95% for a range of 1 nmi for an appreciable fraction of the testing time. During the worst testing conditions encountered, the range at which this detection likelihood occurred was sufficiently large to demonstrate feasibility and to recommend a continuation of the development effort for this approach. A series of recommendations for improving system performance and obtaining the additional information needed to characterize that performance are included in Paragraphs 6.2 and 6.3.

6.2 IMPROVEMENTS IN SYSTEM PERFORMANCE

It is apparent from Figures 18 and 19 that an increase in the effective range of an optical IR is necessary if it is to completely meet the COPAG specification for detection. Such an increase may be obtained by making a series of improvements to the PWI device. Such improvements can be made to both the PWI device itself and to the strobe light from which the PWI receives its signal. It is reasonable to stipulate that the device must operate with most, if not all, existing strobes. Improvements to the PWI should, therefore, be considered as the primary and direct means of increasing range sensitivity. However, on a long term basis, improvement of PWI system performance is also achievable by the generation of specifications for strobe lights as the cooperative element in PWI systems with regard to strobe characteristics presently unspecified. Such characteristics include: peak intensity, pulse to pulse stability both with regard to amplitude and spacing, and pulse rise time.

Specific improvements in the PWI device include decreasing system noise and the resulting threshold levels as well as improving the signal quality. Decreases made in system noise will allow the threshold to decrease, increasing range sensitivity while keeping the false alarm rate constant.

Specific improvements include:

a. optimizing the optical filters used with the PWI detectors, such that the noise level due to background radiation is minimized with regard to the signal level.

b. optimizing the electrical filter with regard to center frequency and bandwidth to improve the received signal to noise ratio. Improvements in signal allow increased range sensitivity for a fixed threshold while decreases in noise allow a corresponding reduction of the threshold level.

c. reducing noise due to microphonic and electromagnetic interference effects in the system. This may be accomplished by amplifier and detector re-design and improving the mechanical mounting of the detectors.

d. reducing amplitude variations of the received signal.

Lobing of the beam and sensor patterns of the strobe beacon and PWI significantly increased signal variations measured during flight tests and caused a reduction of the cumulative probability of detection with range. Minimizing lobing effects will reduce the signal variagion to a level determined by scintillation and strobe light intensity variations. This reduction will increase the cumulative probability of detection versus range at 1 nmi.

Considering changes to the strobe characteristics, an increase in the peak radiated power of the light used in these tests would have resulted in an inproved PWI range sensitivity. Increasing pulse repetition frequency for a given light intensity would increase effective range as a function of closure rate, because the present system requires three pulses before an alarm is generated. Similarly, some ambiguity exists with regard to the variety of methods by which the system logic could be improved. For instance, increasing the required number of signals received before an alarm is issued would decrease false alarms allowing a lower threshold setting resulting in an increase in range sensitivity. The net gain in range sensitivity however, would not exceed a few tenths of a mile and the resulting time delay for alarm would cancel the gains.

In summary, major improvements are likely to be obtained by those techniques which reduce system noise and minimize signal fluctuations due to detector pattern variations. Additional gains can be realized by improvements resulting from the specification of strobe parameters now unspecified.

6.3 FUTURE FLIGHT TESTING

The test results described do not demonstrate that optical PWI will work under all conditions. To establish this, measurements are needed to verify the analytic model and its sub-elements, scintillation effects, background effects, etc., in greater detail. Any future testing should measure signal and noise statistics under a larger selection of ranges, background and atmospheric conditions.

For future flight tests, the sample rate should be increased beyond one second to obtain data more quickly and to minimize flight time. A quick look capability for the data analysis is mandatory for future tests. The signal and noise statistics should be collected directly by sampling, instead of using a threshold device. This will enable measurements to be made where the signal and noise level may be of the same magnitude. Finally, the experiments conducted should have provisions for measurement of background noise statistics directly as well as a measurement of the resultant statistical fluctuation of the threshold level. The background conditions should be carefully selected to ensure that all possible conditions are measured including both steady state noise due to a combination of relative sun angle and internal noise as well as possible impulsive effect due to windshield glint, water reflections and other radiation pulses.

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