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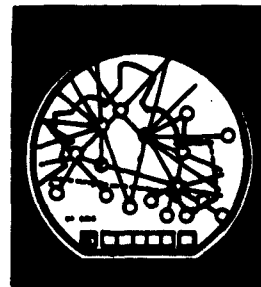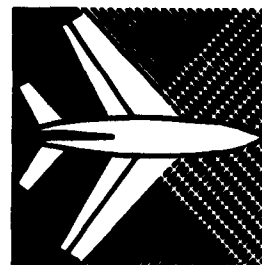
FINAL REPORT

Project No. 110-505V

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EVALUATION OF AN

OMNIDIRECTIONAL INTERROGATING

METRIC WAVE

PILOT WARNING INSTRUMENT

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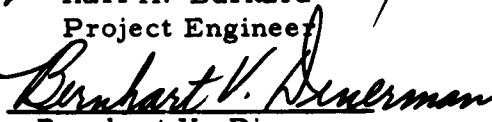
FEDERAL AVIATION AGENCY

Systems Research & Development Service

EVALUATION DIVISION

Atlantic City, New Jersey
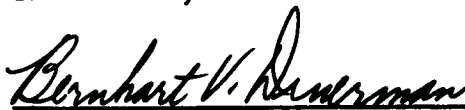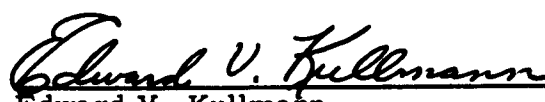
FINAL REPORT

EVALUATION OF AN OMNIDIRECTIONAL INTERROGATING
METRIC WAVE PILOT WARNING INSTRUMENT

PROJECT NO. 110-505V

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"This report is approved for submission to the Director, Systems Research
and Development Service. The conclusions and recommendations are those
of the Evaluation Division, based solely upon its own work as reported herein. "

Chief, Evaluation Division

February 1963

FEDERAL AVIATION AGENCY
Systems Research and Development Service
Evaluation Division
National Aviation Facilities Experimental Center
Atlantic City, New Jersey

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LIST OF ILLUSTRATIONS

ABSTRACT

A Pilot Warning Instrument (PWI), developed by Motorola, Inc.,
Riverside, California, under Contract FAA/BRD-248, was tested
to evaluate the technical feasibility of an omnidirectional interro-
gating metric wave technique for PWI applications, and to determine
the operational utility of this PWI concept as a pilot aid for collision
prevention.

The PWI was subjected to laboratory, field, and airborne tests to
determine the altitude discrimination capability, range and bearing
accuracies, and reliable communication range of the equipment.

The results of the evaluation demonstrated inherent technique
weaknesses in the form of self-generated, ground-reflected inter-
ference signals that seriously compromised the system performance.
It was concluded that the PWI techniques implemented in the evaluation
model were unsuitable for airborne use as a collision prevention device.

PURPOSE

Systems Research and Development Service efforts to develop
a practical Pilot Warning Instrument for the aviation community
are based upon Project Beacon recommendations which recognize
the desirability of the concept and support the investigation of all
Pilot Warning Instrument techniques.

The purposes of the project assignment were to determine
the technical performance of an omnidirectional interrogating metric
wave Pilot Warning Instrument and to determine the worth of the
pilot warning information with respect to the mid-air collision
prevention problem.

An appraisal of the Pilot Warning Instrument technical per-
formance would be based upon the system range and bearing accura-
cies, communication coverage, altitude discrimination capability,
and susceptibility to interference. The worth of the system in
reducing collision hazards would be based upon the enhancement
of a pilot's ability to visually acquire an intruding aircraft when
provided with the Pilot Warning Instrument information.

INTRODUCTION

Background

Based upon statistics concerning reported near collisions compiled by the Bureau of Flight Standards,[1] most potential collision situations occur during daylight hours in periods of good visibility. The major reason for these near-misses is the inability of the pilot to observe the approaching aircraft at a sufficient range to alleviate the potential collision situation. Under clear-sky conditions, the small size of the incoming aircraft profile against a forward hemisphere search field, together with the narrow field-of-view of the pilot's vision and his normal cockpit workload, makes detection with the unaided eye very difficult.

Experimental data reveal that the pilot's discerning capability can be considerably increased if he is prewarned of the relative approach angle of the incoming aircraft so that he can limit his visual search to a narrow sector surrounding the anticipated aircraft approach angle[2]. The increased visual detection range under this condition can materially reduce the incidence of near-misses.

One portion of the airborne collision prevention program in the Federal Aviation Agency (FAA) is concerned with the development of airborne devices that would alert the pilot to a potential collision at a distance beyond the threshold detection range with the unaided eye. With this information, the pilot would be able to observe the threat aircraft at or near the visual detection threshold range, thereby providing more time for evasive action. An equipment for this application is called a Pilot Warning Instrument (PWI). Given an appropriate warning by the PWI, the interpretation of the threat situation and the initiation of an avoidance maneuver would be the responsibilities of the pilot.

This report relates to the evaluation of a particular PWI developed for the Systems Research and Development Service by Motorola, Inc., under Contract FAA/BRD-248. The equipment was intended to be a low-cost, lightweight, all-weather PWI and utilized an omnidirectional interrogating metric wave technique previously proposed by the Contractor.

[1] Federal Aviation Agency, Bureau of Flight Standards, "Compilation of Reported Near Midair Collisions in 1959," dated March 15, 1960.

[2] Wayne D. Howell, "Determination of Daytime Conspicuity of Transport Aircraft," CAA Technical Development Report No. 304, May 1957.

Project Scope

Under the provisions of Project No. 110-505V (formerly 305-5-2V), the Evaluation Division was directed to perform an engineering evaluation to determine the feasibility of the omnidirectional interrogating metric wave PWI technique exemplified in the development model. Specific tests were to be performed to determine PWI altitude discrimination capability, bearing and range accuracies communication coverage within the 25-nautical-mile (NM) display range, the worth of the PWI display to the pilot with respect to the collision-prevention problem under VFR conditions, and the effects of interference on the PWI.

Laboratory tests to determine the altitude discrimination capability of the PWI were performed in the Standards and Calibration Laboratory of the Technical Services Division. Field tests to determine the PWI bearing accuracy were conducted at the Warren Grove Visibility Test Range. Ground-to-air and air-to-air evaluations to determine the PWI range accuracy, reliable communication range and effects of interference on PWI performance were conducted at the National Aviation Facilities Experimental Center (NAFEC), the Warren Grove Visibility Test Range, and in two specially instrumented C-45 type aircraft.

Data acquired from these tests were reduced, correlated, and analyzed to determine the adequacy of the PWI technique for the development of a low-cost, lightweight, all-weather Pilot Warning Instrument for the aviation community.

Evaluations originally contemplated to determine the communications coverage pattern surrounding the interrogating aircraft, and the enhancement of a pilot's discerning capabilities when provided with the PWI information, were canceled due to PWI deficiencies caused by self-generated interference from ground-reflected signals.

DISCUSSION

Description of Equipment

The Motorola PWI concept is based on signal phase comparisons for azimuth determination, and pulsed radar techniques for range determination. The PWI developed to implement this concept is a cooperative, pulse-modulated, frequency-modulation (FM) system operating at a carrier frequency of 135.5 megacycles (Mc) and is comprised of one transmitting and three receiving antennas, a receiver-transmitter unit, a data processor unit, a barometric coder-decoder unit, and a display unit. The PWI weighs 18 pounds, is 0.75 cubic foot in volume, and consumes 80 watts of 28-volt DC power. Appendix I is a detailed description of the PWI theory of operation.

The three receiving antennas shown in Fig. 1 are mounted beneath the aircraft in the pattern of an isosceles triangle. The spacing between the antennas is slightly less than a quarter wave-length at the 135.5 Mc operating frequency. The single transmitting antenna also shown in Fig. 1 is mounted atop the aircraft.

The receiver-transmitter (R-T) unit is comprised of a programmer that generates a 20 cycle (50,000 microseconds) PWI repetition rate, and within one cycle controls a 300 microsecond (Msec) interrogation pulse from the carrying aircraft, a sweep signal for range measurement purposes, and 49,700 Msec period for the reception of and the replies to signals transmitted from other aircraft; an FM transmitter that produces the 300 Msec signals which interrogate other aircraft, as well as the 15 Msec signals that reply to interrogations from other aircraft; two receivers connected to the two transverse antennas to determine the orientation of the incoming wave front, plus a third receiver and antenna as parts of a system to resolve the resulting 180° ambiguity in direction of signal arrival at the antennas; and discriminators that provide "video" and "gate" signals for the PWI data processor unit.

The outputs of the two receivers feed a left-right discriminator. The video signal from the left-right discriminator contains the relative bearing and range information. Since the bearing is determined by phase comparisons, the video signal follows a sine curve function with the bearing intelligence depending upon the amplitude and sign of the video signal. Range is determined by the elapsed time between the PWI interrogation and the reception of the replying signal.

The outputs of the third receiver and one of the two receivers used for phase comparisons are connected to a fore-aft discriminator that furnishes the gate signal only when the measurement of the electrical phase difference between these two receivers indicates that the incoming wave front is being transmitted from an aircraft in the forward hemisphere of the carrying aircraft. Signals from aircraft in the rear hemisphere do not produce gate signals.

3

FORWARD

20.5 IN.

10.25 IN.

20.5 IN.

ANT. 1

ANT. 2

ANT. 3

℄
AIRCRAFT
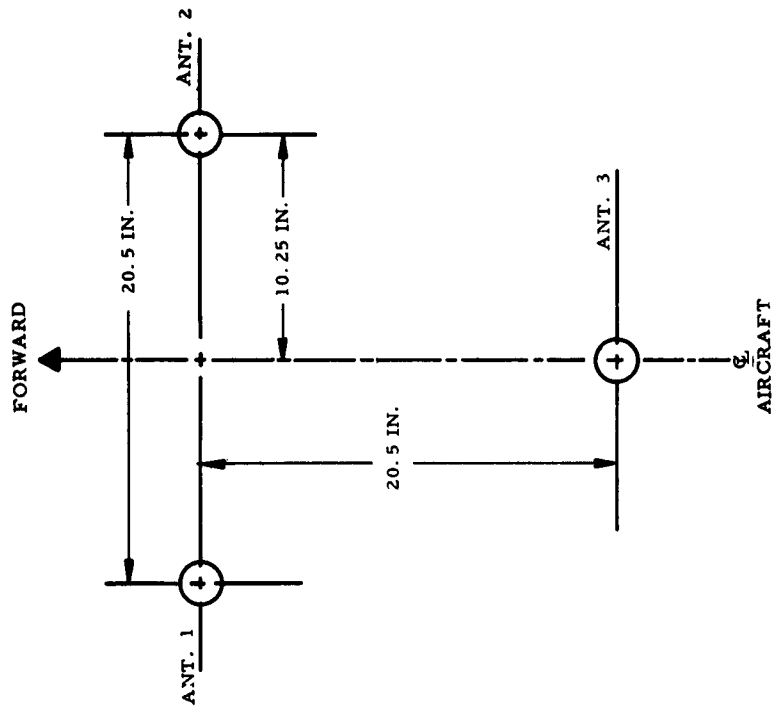
A - ANTENNA INSTALLATION ON
PROJECT AIRCRAFT

B - RECEIVING ANTENNA GEOMETRY

FIG. 1   AIRCRAFT ANTENNA CONFIGURATION

The data processor unit receives the video and gate signals from the R-T unit, and processes and limits the information for display by means of standard amplifier, gate, trigger, and coincidence circuits. Since the PWI system possesses the inherent capability to provide bearing coverage for a full 360°, the gate and video signals resolve the fore/aft bearing ambiguity by processing bearing information only when these two signals are coincident. With the gate signal only available for coincidence when the received signal is from an aircraft in the forward sector, the PWI display unit presentation of intruder aircraft relative position is limited to the forward hemisphere. In addition, a sweep signal, starting at the end of the PWI interrogation pulse is used to electronically limit the range information for the pilot to 25 NM.

The barometric coder-decoder unit theoretically provides a degree of discrimination to the PWI by completing the PWI communications link only when the cooperating aircraft are within a certain altitude band. An altitude code is generated by a pressure-sensitive oscillator in the barometric coder-decoder unit that modulates the frequency of the PWI interrogation and/or reply signals as a function of pressure altitude. Altitude-coded interrogations from other aircraft are received, decoded, and fed to a pressure-sensitive tuned circuit in the barometric coder-decoder unit for comparison with the altitude-coded oscillator frequency of the carrying aircraft. For situations where the two frequencies are coincident, a 15 Msec reply signal is generated and transmitted to complete the communications link between aircraft.

The PWI display unit shown in Fig. 2 consists of a display that provides forward azimuth information in six equal 30° sectors, and range information in five equal 5-mile range sectors to 25 NM for a total of 30 segments. A particular segment is illuminated by a lamp that is energized by a pulse from the bearing and range circuitry, denoting an intruder position relative to the nose of the PWI-equipped aircraft.

The various components comprising the PWI are shown in Fig. 3.

Test Procedures and Results

1. Frequency Response, Repeatability, and Response Similarity of Barometric Coder-Decoder Units: The tests to determine the frequency response, repeatability, and response similarity of the PWI barometric coder-decoder units were conducted in the laboratory. A block diagram of the instrumentation arrangement is shown in Fig. 4.

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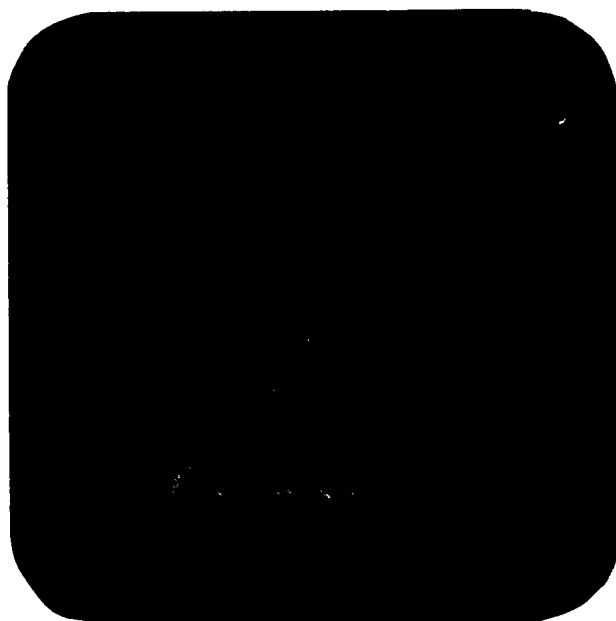
FIG. 2   PWI DISPLAY UNIT

A. PILOT WARNING INSTRUMENT

B. PILOT WARNING INSTRUMENT WITH DUST COVERS REMOVED

FIG. 3   PWI EQUIPMENT (LESS TRANSMITTING ANTENNA)

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                    ┌─────────────────┐
                    │    VACUUM       │
                    │    PUMP         │
                    └────────┬────────┘
                             │
                             ▼
┌──────────────┐   ┌─────────────────────┐   ┌──────────────┐
│              │   │  HAAS INSTRUMENTS   │   │              │
│   VACUUM     │   │  ABSOLUTE PRESSURE  │   │   PRESSURE   │
│   PUMP       │   │     MERCURIAL       │   │   RESERVOIR  │
│              │   │     BAROMETER       │   │              │
│              │   │     TYPE A-1        │   │              │
└──────┬───────┘   └──────────┬──────────┘   └──────┬───────┘
       │                      │                     │
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       ▼           ┌─────────────────────┐          ▼
                   │  HASS INSTRUMENTS   │
                   │                     │
                   │     CONTROLLER      │
                   │                     │
                   │     TYPE PSC-2      │
                   └──────────┬──────────┘
                              │  ⎧ CONTROLLED
                              │  ⎨ PRESSURE
                              │  ⎩ INPUT
                              ▼
                   ┌──────────────────┐      ┌──────────────┐
                   │   BAROMETRIC     │      │  HEWLETT-    │
                   │   CODER-         │◄─────│  PACKARD     │
                   │   DECODER        │      │  721 A       │
                   └──────────────────┘      │  POWER       │
                                             │  SUPPLY      │
                                             └──────────────┘
                   ┌──────────────────┐
                   │   HEWLETT-       │
                   │   PACKARD        │
                   │   522B DIGITAL   │
                   │   COUNTER        │
                   └──────────────────┘
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FIG. 4   EQUIPMENT ARRANGEMENT FOR ALTITUDE-FREQUENCY
         TESTS OF BAROMETRIC CODER-DECODER UNIT

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The Type A-1 barometer, vacuum pumps, nitrogen pressure reservoir, and Type PSC-2 controller served as a composite unit to provide a controlled simulated altitude source. Since the barometric coder-decoder unit was being tested independently of the PWI, an external +18 VDC source was required for operation. The controlled simulated altitude source was coupled to the barometric coder-decoder unit. The output frequency from the barometric coder-decoder unit was monitored on a Hewlett-Packard Model 522B electronic counter. This output frequency was recorded at every 2000-foot increment a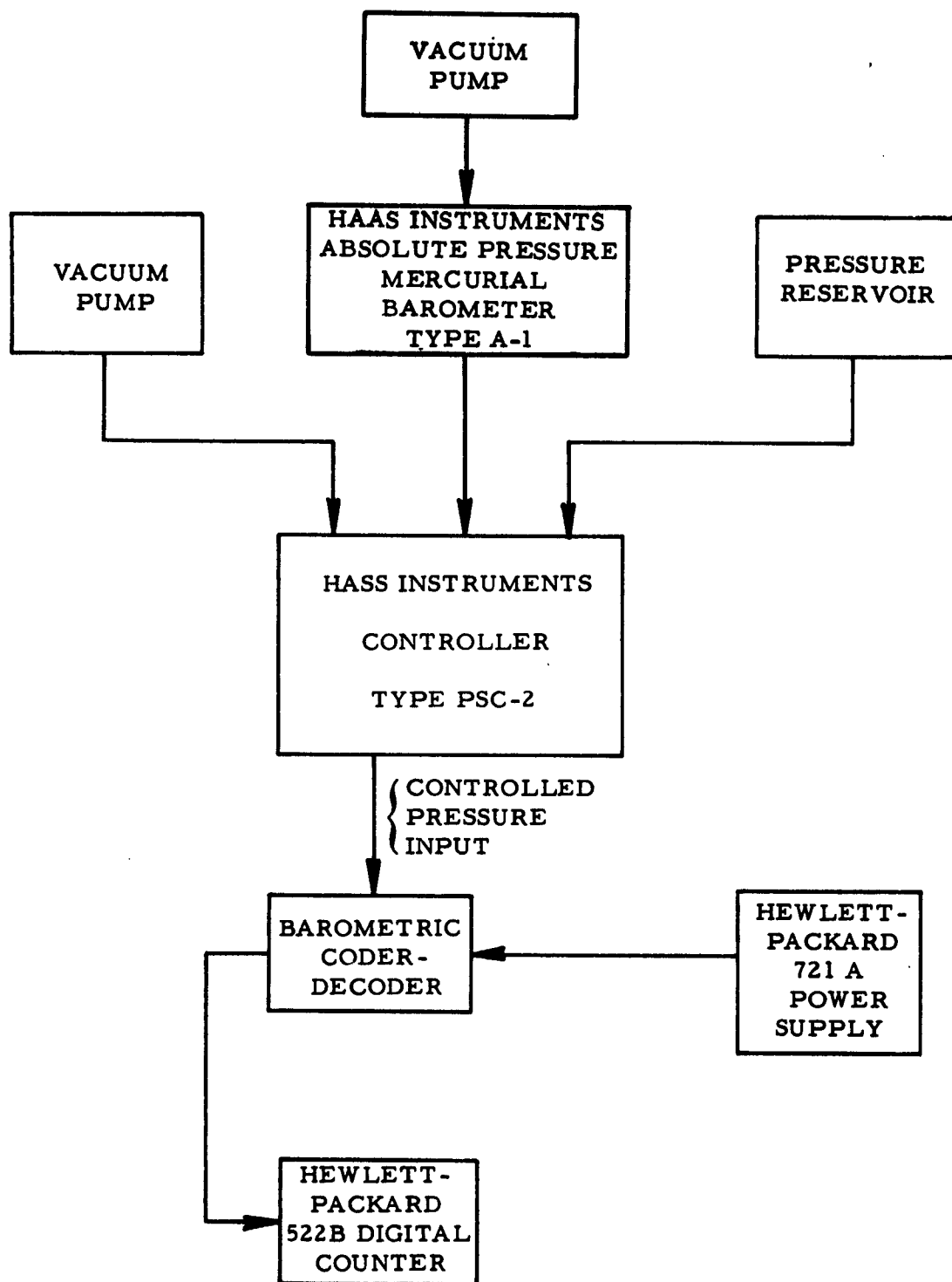s the simulated pressure altitude varied from sea level to 20,000 feet. To obtain the data for determining repeatability and response similarity, each of the two PWI barometric coder-decoder units was subjected to two altitude cycles, with one complete cycle comprising altitude changes from sea level to 20,000 feet and return.

The results of the laboratory test to determine the output frequency response versus operating altitude and repeatability of the barometric coder-decoder unit are shown in Fig. . As indicated, barometric coder-decoder Unit A has a repeatable respoi se with negligible hysteresis effects. Unit B is subject to hysteresis effects that result in a variation of approximately 1000 feet at the 20,000 foot operating altitude. Since one of the units possesses the desired degree of repeatability, it is assumed that other units with matching responses can be provided by factory adjustments and/or preferential selection during fabrication.

A comparison of the average frequency response of each unit to show the response similarity between units is made in Table 1.

Simulated Altitude (feet)	Average Barometric Coder-Decoder Unit Output Frequency (kilocycles)		Average Frequency Difference of Unit B (kilocycles)	Average Altitude Difference of Unit B (feet)
	Unit A	Unit B		
Sea Level	41.092	40.770	-.322	-100
2,000	47.829	47.699	-.130	-50
4,000	52.671	52.635	-.036	-50
6,000	56.399	56.499	+.100	+75
8,000	59.325	59.542	+.217	+175
10,000	61.843	62.103	+.260	+250
12,000	64.021	64.291	+.270	+350
14,000	65.809	66.175	+.366	+400
16,000	67.393	67.805	+.412	+500
18,000	68.752	69.239	+.487	+600
20,000	70.000	70.504	+.504	+900

TABLE 1:   RESPONSE SIMILARITY OF PWI BAROMETRIC
           CODER-DECODER UNITS

FIG. 5 ALTITUDE-FREQUENCY CHARACTERISTICS FOR CODER PORTION OF BAROMETRIC CODER-DECODER UNIT

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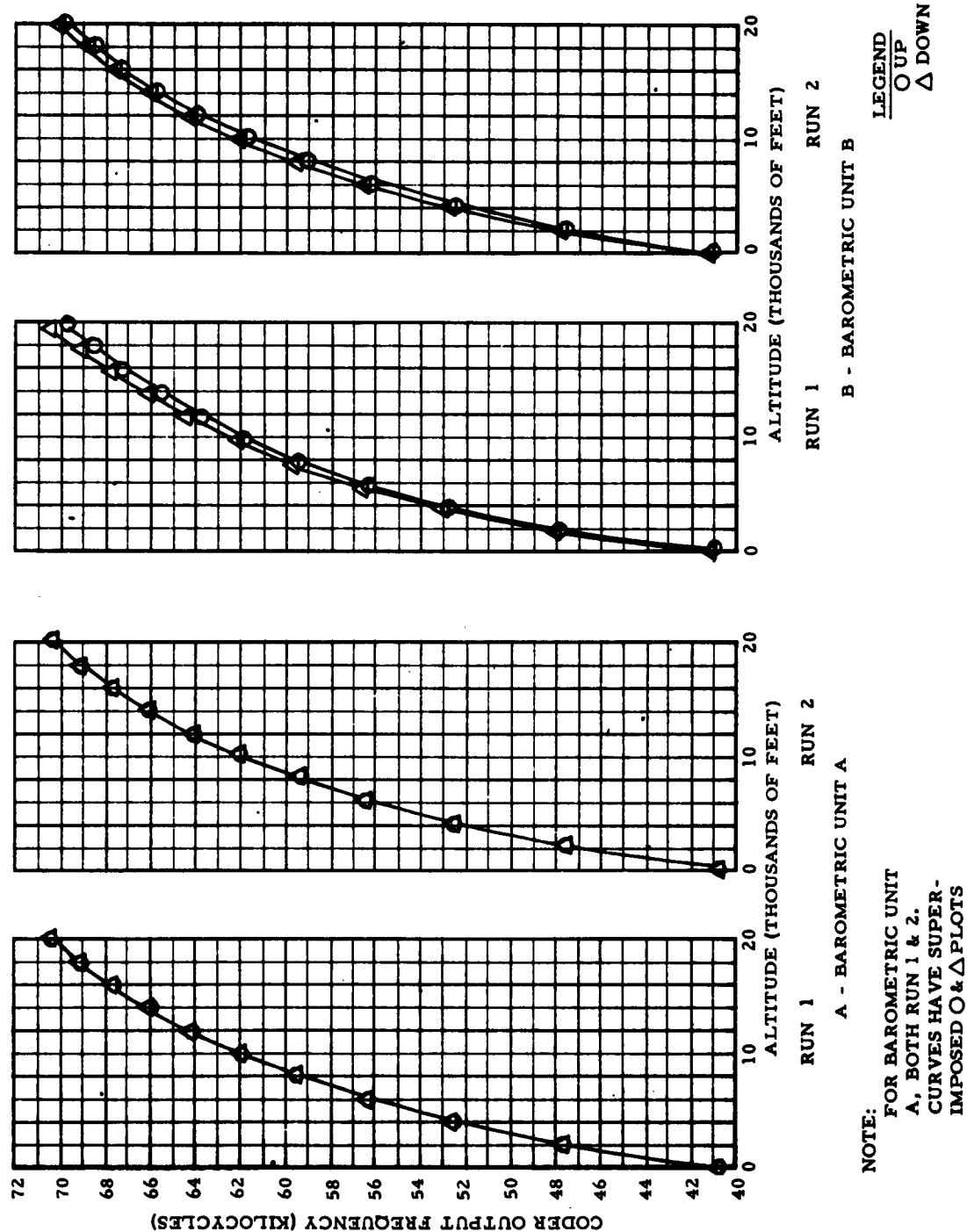
As noted, the maximum frequency difference at the simulated 20,000 foot altitude was 0.504 kilocycles which, when converted to altitude coding of center operating altitude of the Pilot Warning Instruments, resulted in a 900 foot difference. This altitude difference was well within the altitude acceptance band of the PWI at 20,000 feet and as such, provided reliable interrogator-transponder communication.

2. **PWI Altitude Acceptance Band:** A Block diagram of the instrumentation arrangement for determining the altitude acceptance band of the PWI at various center or operating altitudes is shown in Fig. 6. This laboratory test involved the operation of one complete PWI system to interrogate and receive a reply from a PWI transponder operating from a remote position. The controlled simulated altitude source previously described was coupled to the barometric coder-decoder unit of the complete PWI to FM code the interrogation according to the selected operating altitude. At the transponder installation position, another barometric coder-decoder unit decoded the interrogation, and initiated a reply when a near co-altitude situation existed. The barometric coder-decoder unit of the PWI transponder was connected to a portable air data tester that furnished pressure input to simulate altitude. The pressure to the PWI transponder was regulated to provide simulated center altitudes of 0, 5000, 10,000, 15,000 and 20,000 feet. Starting from the same center altitude, the pressure to the barometric coder-decoder unit of the complete PWI was varied to provide incremental simulated altitude changes both above and below the fixed center altitude of the PWI transponder. The display unit presentation at the complete PWI was monitored and notations made of the altitude differences when the display lights were on 100, 50, and 0 per cent of the time.

The test data to determine the altitude acceptance band of the PWI were based upon an operator's estimate as to when the PWI display lights denoting target position were on 50, and 0 per cent of the time as the altitude difference between the two PWI systems was gradually increased. The results are shown graphically in Fig. 7, which denotes the PWI altitude acceptance band above and below a fixed center altitude as a function of a center altitude. The curves indicate the PWI altitude acceptance band for situations when the display lights were on 50 and 0 per cent of the time. Both curves are based on the average of readings from three runs. As an example, the transponder PWI operating at a 20,000 foot altitude processed and displayed 50% of the time signals from the complete PWI operating at altitudes 5,500 feet and 7,500 feet respectively above and below the position of the transponder PWI. For this situation, the total altitude acceptance band was 13,000 feet.
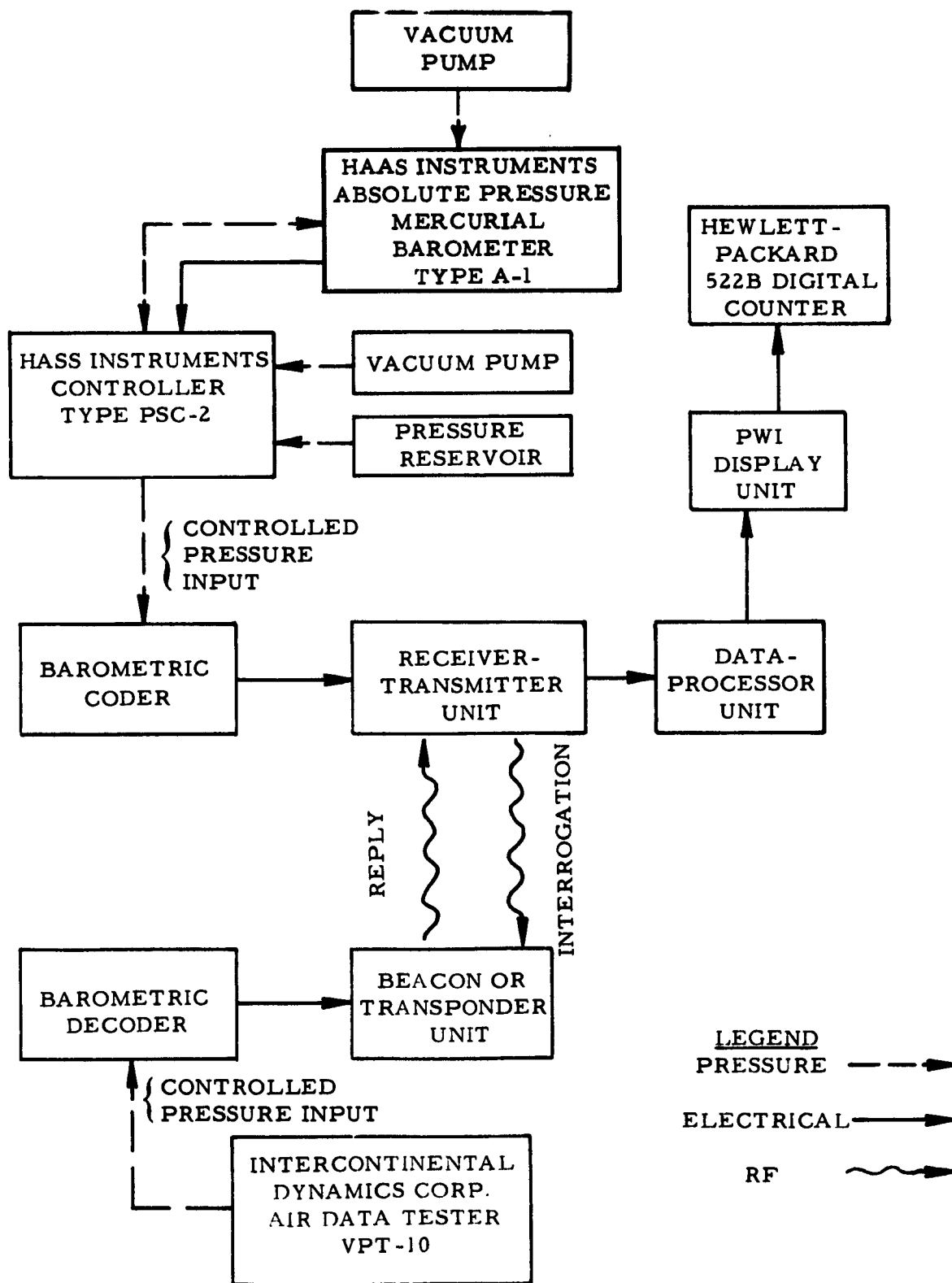
**FIG. 6 EQUIPMENT ARRANGEMENT FOR MEASUREMENT OF PWI
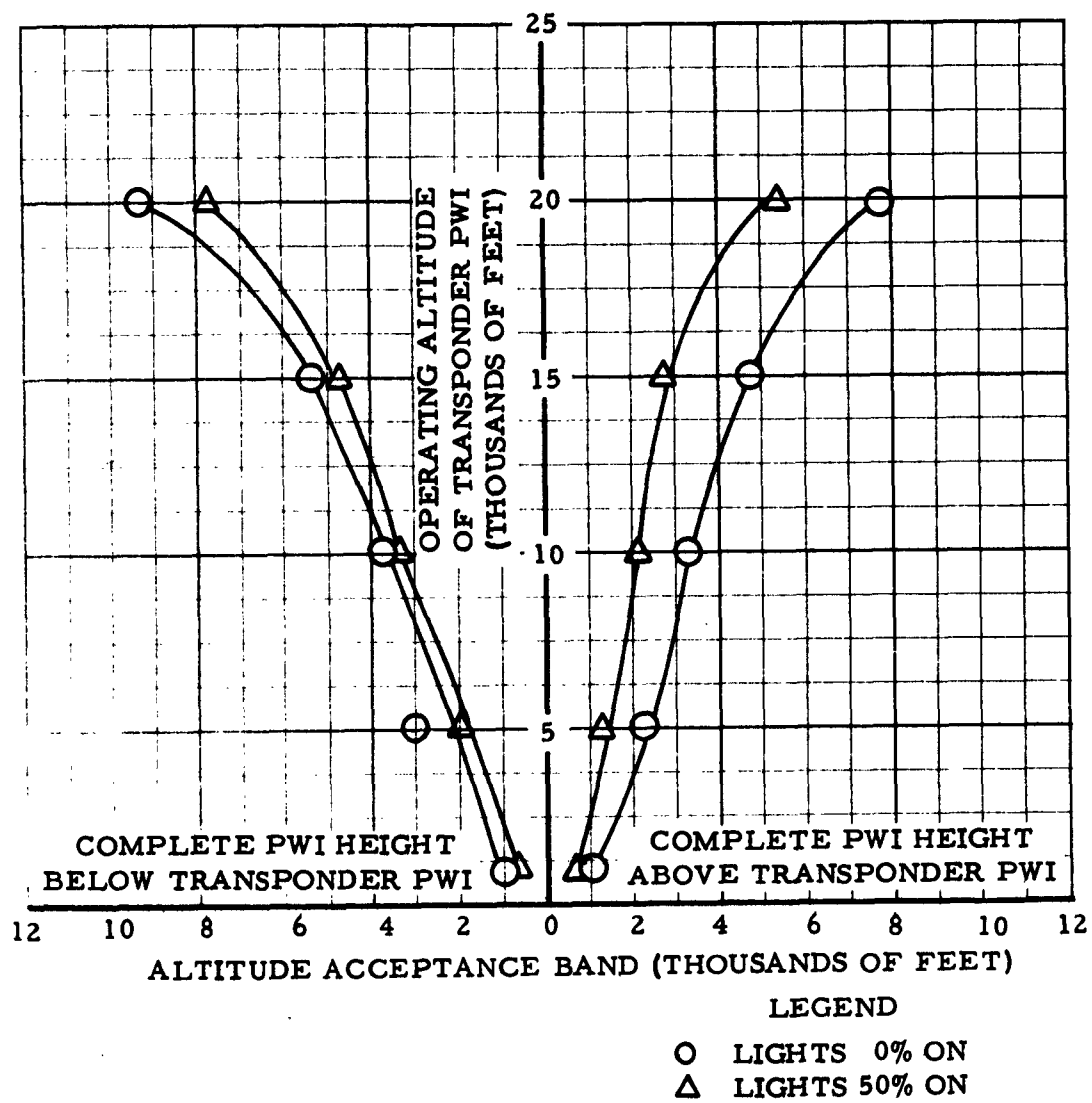ALTITUDE ACCEPTANCE BAND**

FIG. 7 ALTITUDE ACCEPTANCE BAND OF PWI EQUIPMENT

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For the cases when both PWI units were operating at the same simulated altitude, the display lights were on 100% of the time. As shown, the altitude acceptance band widened considerably at the higher altitudes. This phenomenon was due to the response of the barometric coder-decoder unit which is approximately linear with respect to pressure rather than altitude.

3. PWI Bearing Accuracy: The test to determine the PWI bearing accuracy was conducted at the Warren Grove Visibility Test Range and required project equipment and instrumentation in and on the main building and at a remote site approximately 2.5 NM removed. The Test Range was selected for these ground-to-ground tests in order to provide a quiet electromagnetic radiation area and relatively flat terrain with a minimum of physical obstructions. These requirements were necessary to minimize the effects of external radiation interference and multipath reflections on the PWI performance. The physical configuration of the main building is shown in Fig. 8. A block diagram of the project equipment arrangement is shown in Fig. 9 and consisted of a complete PWI unit and auxiliary signal recording and monitoring instrumentation. A rotatable ground plane approximately 66 inches in diameter with the three PWI receiver antennas attached, and a fixed ground plane approximately 44 inches in diameter with the PWI transmitter antenna attached were mounted atop the main building, as shown in Fig. 10. A PWI transponder was located at a remote site approximately 2.5 NM from the main installation. The installation at the remote site is shown in Fig. 11 and consisted of a PWI transponder, appropriate antennas attached to 44-inch diameter ground planes, and power sources for PWI operation. The PWI stub antennas shown in Figs. 10 and 11 were made more identifiable against the sky background by retouching the original photographs.

Prior to the collection of test data, the PWI communication link between the main building and the remote site was placed in operation. An interrogation from the transmitter on the main building triggered a reply from the transponder at the remote site. Signals from the transponder were received at the receiver antenna system at the main building and processed for signal display on the PWI display unit and the instrumentation oscilloscope. Video, gate, and display unit indications were observed to verify that the signal channels were normal with no spurious signals from interfering radiation sources. In addition, the mechanical 000° bearing position of the PWI receiver antenna system was optically bore-sighted with the PWI transponder antenna at the remote site and the PWI receiver system electrically calibrated for a 000° bearing indication on the PWI display unit and the video signal.
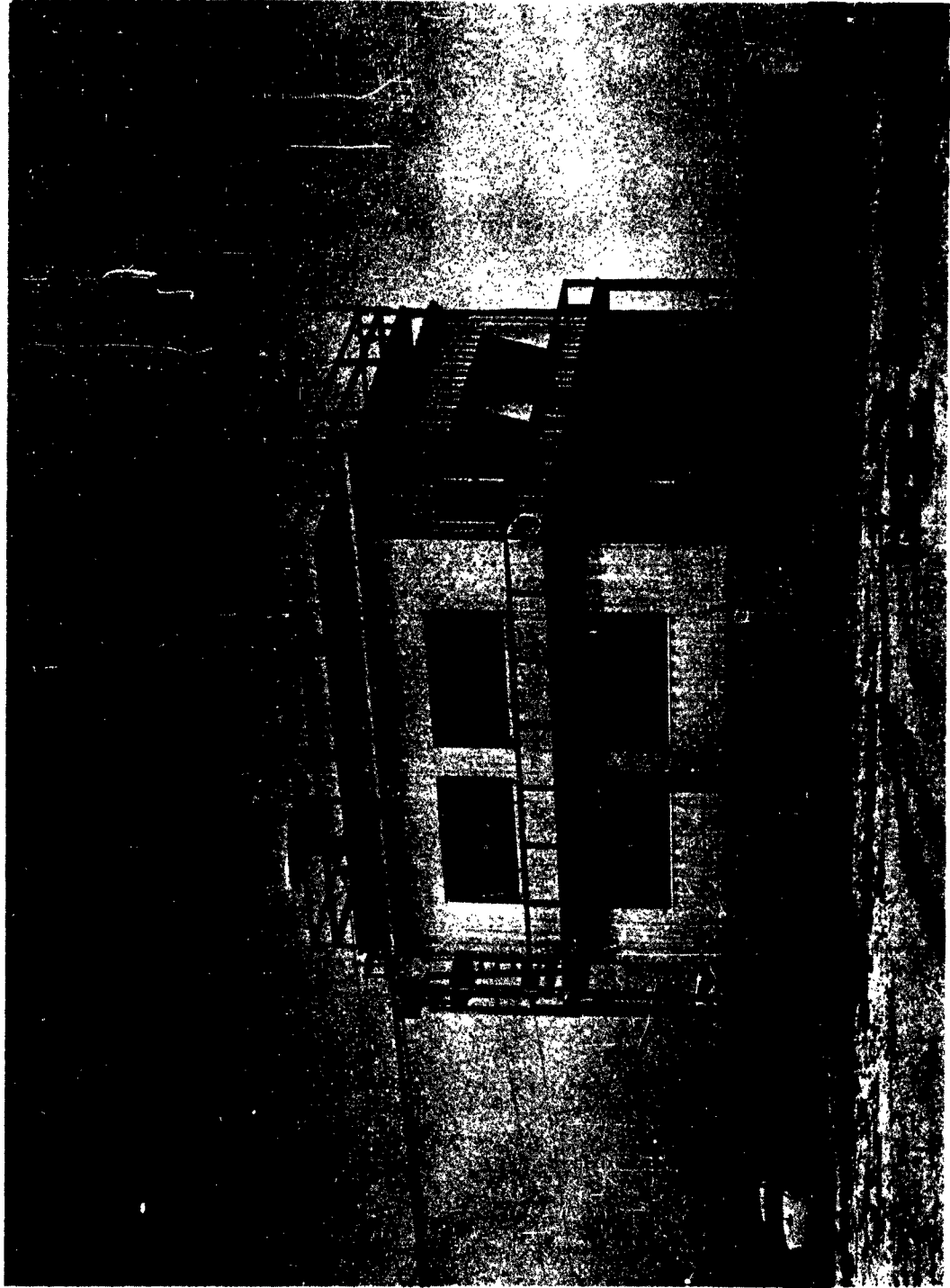
14

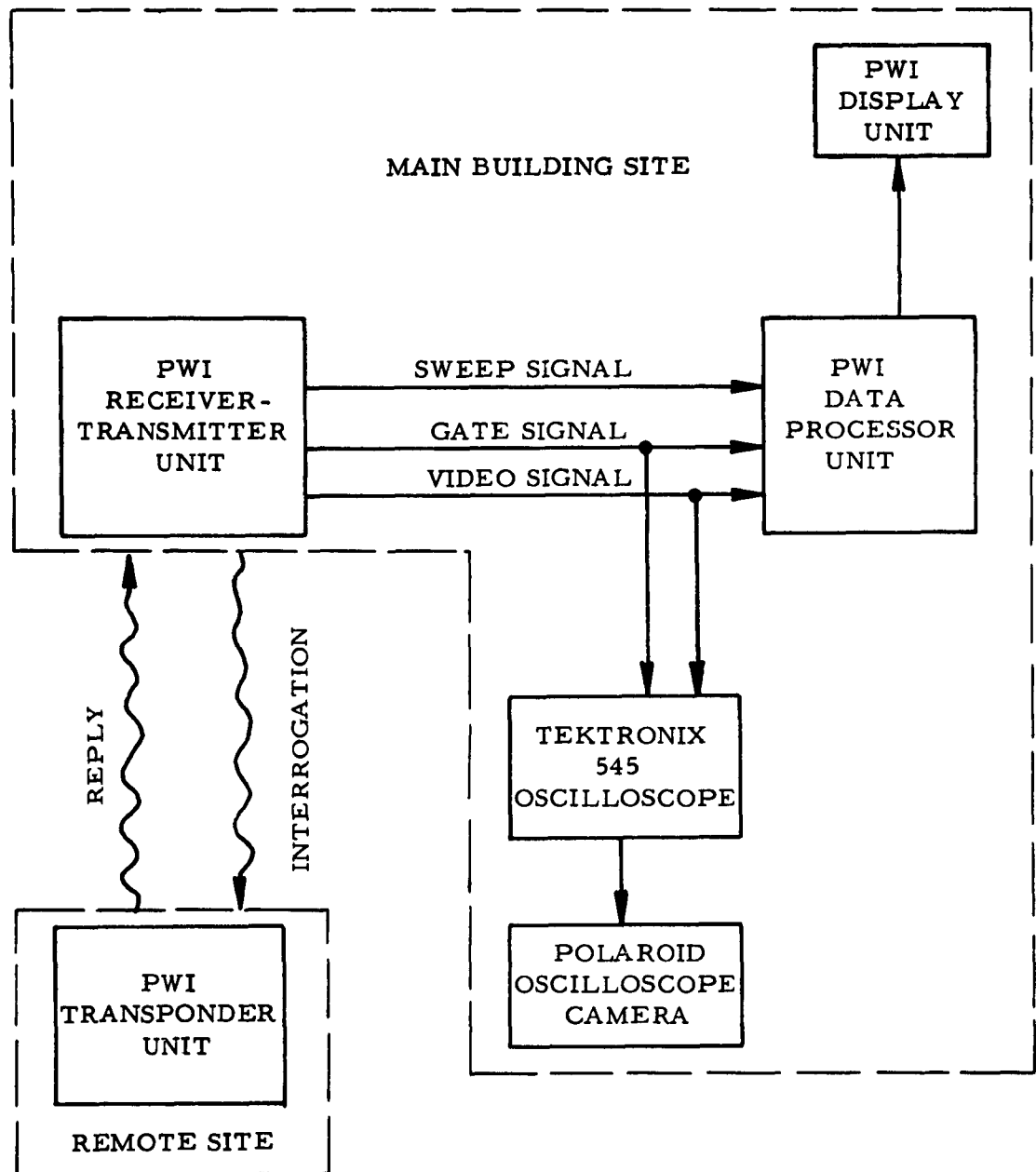FIG. 8 MAIN BUILDING AT WARREN GROVE VISIBILITY TEST RANGE

FIG. 9 EQUIPMENT ARRANGEMENT FOR BEARING ACCURACY TESTS

FIG. 10 ANTENNA INSTALLATION ON MAIN BUILDING OF
WARREN GROVE VISIBILITY TEST RANGE

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TRANSMITTING ANTENNA

RECEIVING ANTENNAS

TRANSPONDER UNIT

FIG. 11 REMOTE SITE INSTALLATION FOR BEARING ACCURACY TESTS

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For data collection, the rotatable PWI receiver antenna system atop the main building was rotated from 0° through 360° in 10° intervals. At each position, a photograph of the video and gate oscilloscope traces was made, and the PWI display unit presentation recorded.

The results of the tests to determine the PWI bearing accuracy from the continuous bearing information in the video signal and the segmented bearing presentation on the PWI display unit are shown in Figs. 12, 13, and 14. Figure 12 shows the video output of the R-T unit as a function of the transponder angle relative to the forward position of the receiving antenna system. A true sine curve is also plotted for comparison purposes. Since the PWI bearing determination is based upon a phase angle measurement of the received signal, perfect PWI receiver and discriminator sections would give an output coinciding with the sine curve. Figure 13 is a plot of the PWI bearing error in degrees as a function of ground plane angle for the two R-T units used in the flight test program when compared to a theoretically perfect R-T unit possessing a sine curve response. Figure 14 is a plot of the lighted PWI bearing sectors versus relative target position for 10° incremental changes in the target bearing. As shown, the response was related to the accuracy of the bearing information contained in the video signal. A review of the bearing accuracy measurement data revealed that the PWI bearing error became progressively larger and/or became more erratic as the target relative position moved from the 000° bearing. Within the forward hemisphere presentation capabilities of the PWI display unit, the bearing errors increased relatively uniformly from zero error at the 000° position to approximately + 10° of error at or near the 060° and 300° relative bearings. From these bearings to the extremes of the forward hemisphere coverage, the bearing errors were nonlinear and erratic, reaching a maximum value of 28° . These errors were manifested by inaccurate bearing information on the segmented presentation of the PWI display unit.

4. PWI Range Accuracy: The test to determine the range accuracy of the PWI was conducted at the Warren Grove Visibility Test Range and involved the utilization of an air-to-ground PWI link. As for the bearing accuracy test, this location was selected to provide an interference-free environment. The installation at the main building was the same as described for the bearing accuracy test except that a photopanel containing a clock and the PWI display unit was added, and provisions made for the simultaneous photographing of the oscilloscope traces of video and gate signals and the photopanel, as shown in Fig. 15. The PWI transponder previously located at the Warren Grove remote site for the bearing accuracy test was installed aboard a C-45 type NAFEC
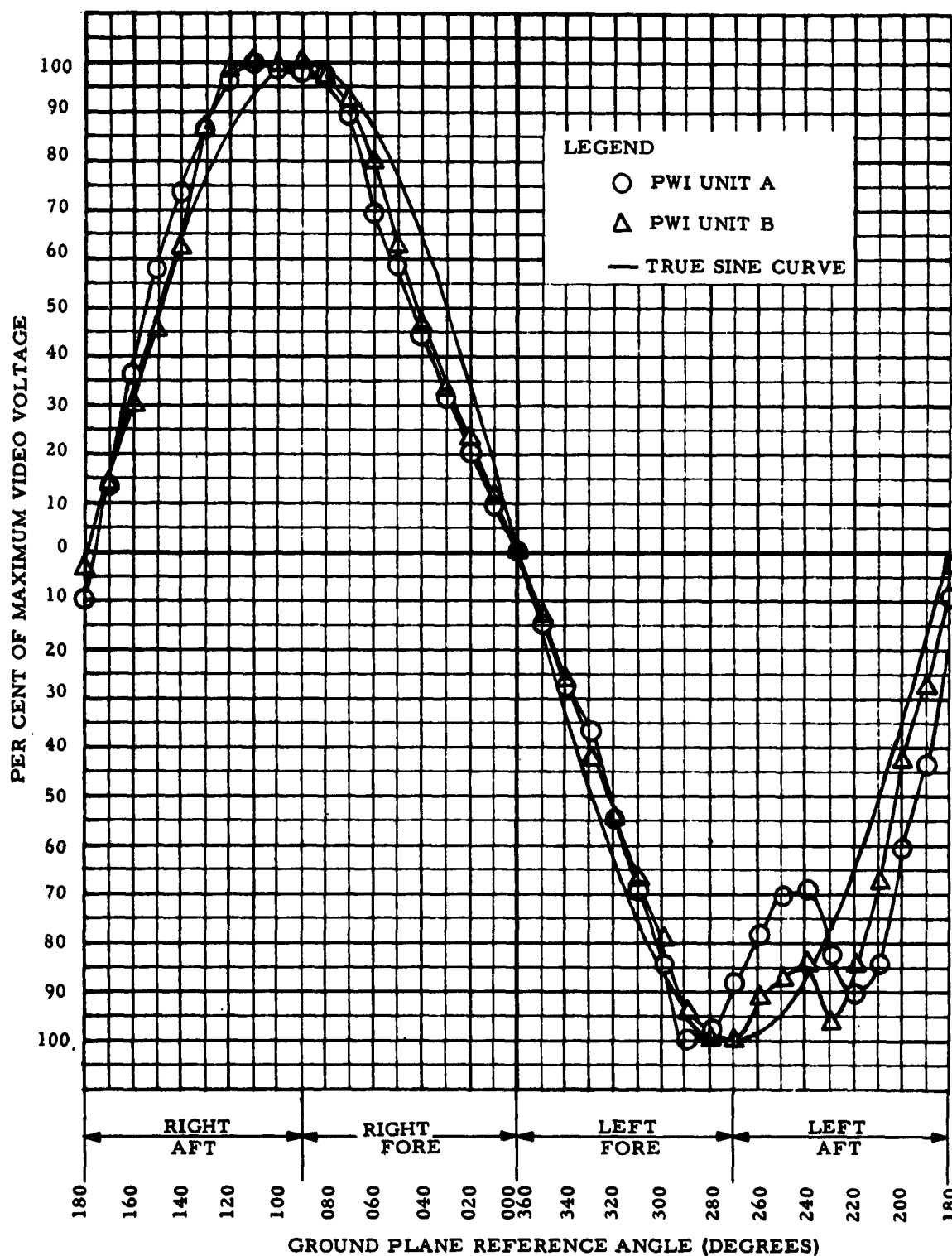
FIG. 12 COMPARISON OF PWI VIDEO BEARING INFORMATION WITH THE GROUND-PLANE REFERENCE ANGLE
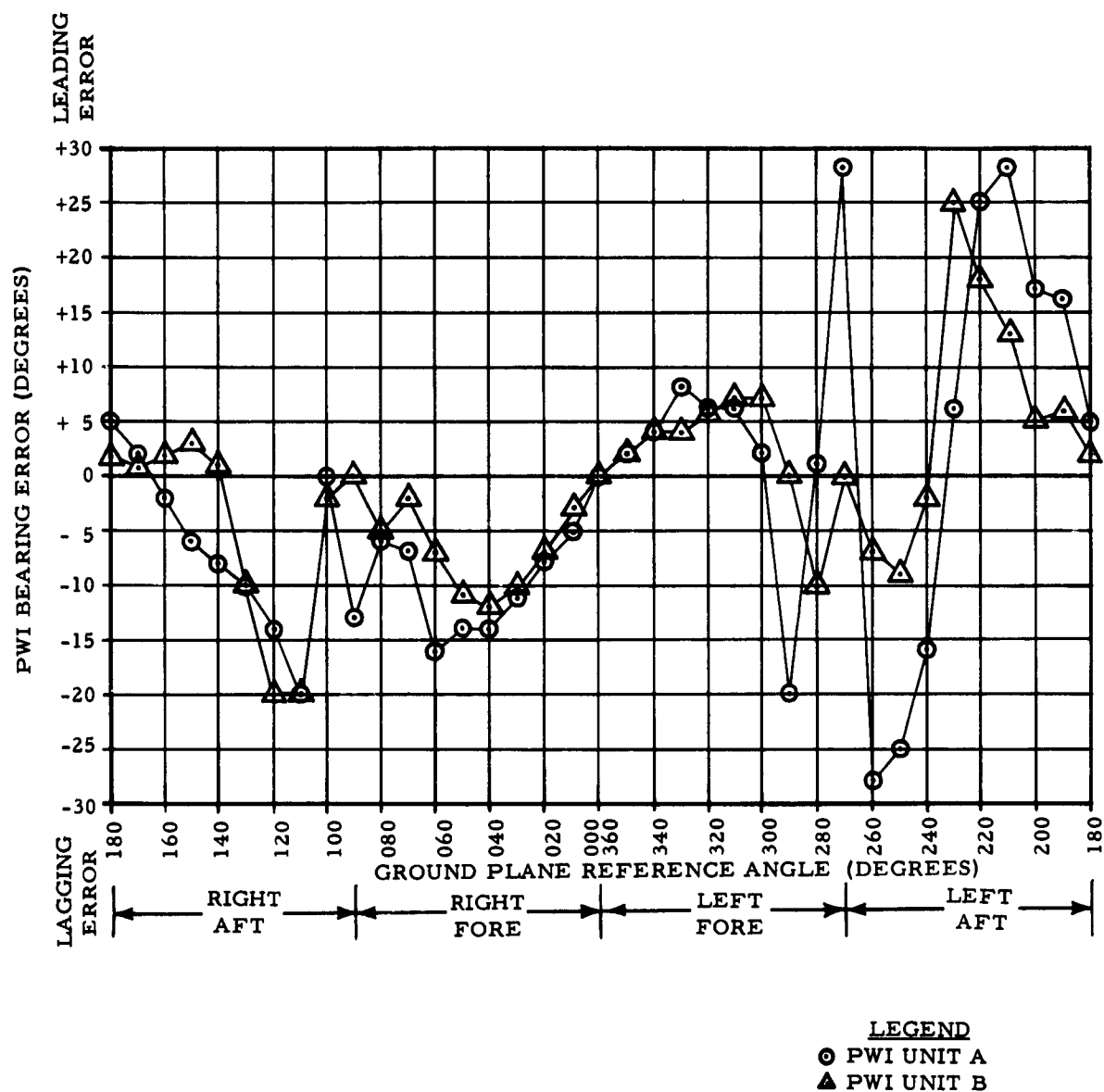
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FIG. 13 PWI BEARING ERROR BASED UPON GROUND-PLANE
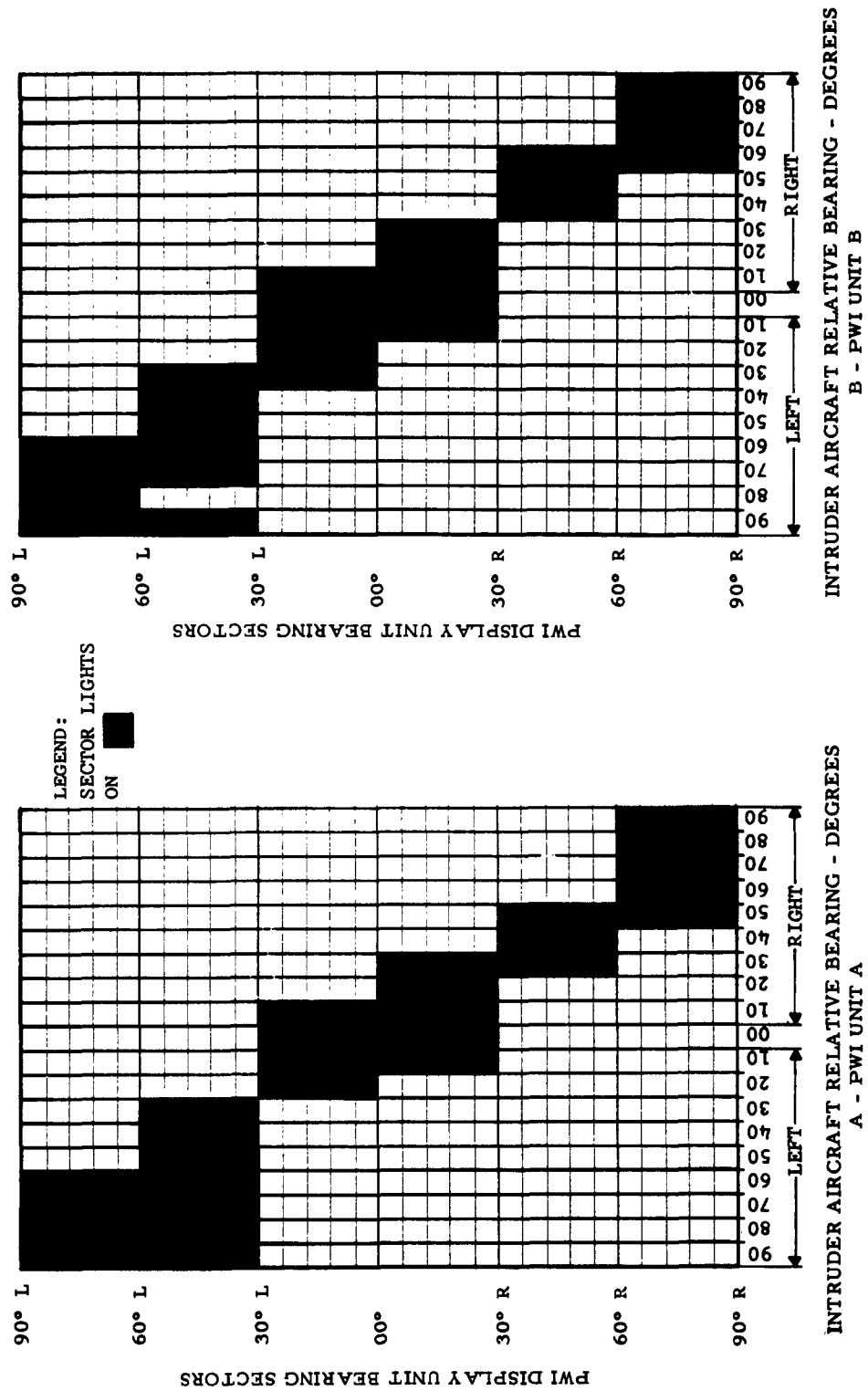REFERENCE ANGLE

21

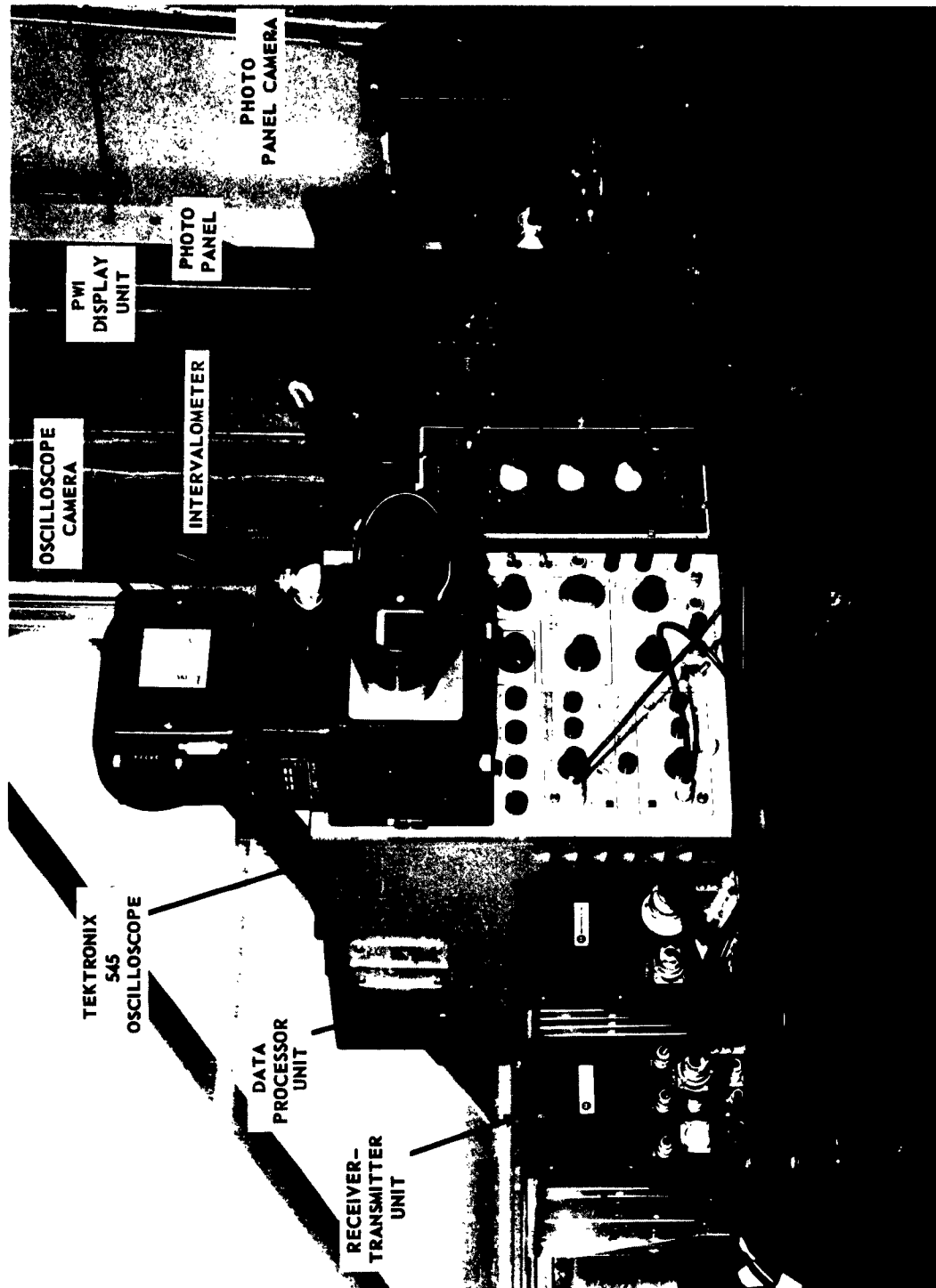FIG. 14   BEARING INFORMATION AS DEPICTED ON PWI DISPLAY UNIT

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FIG. 15   EQUIPMENT ARRANGEMENT IN MAIN BUILDING FOR
RANGE ACCURACY TESTS

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aircraft. Starting at a 30-mile range, 12 runs at altitudes between 1500 and 2000 feet were made over the complete PWI installation in the main building. The aircraft was vectored by an air traffic control specialist at the NAFEC AN/FPN-34 radar site. As the aircraft closed range, photographic data were recorded of the PWI display unit and the oscilloscope traces of video and gate signals at each nautical mile increment of range as reported by ground control radar personnel.

The results of the ground-to-air tests to determine the PWI range accuracy from the continuous range information in the video signal and the segmented range presentation on the PWI display unit are shown in Figs. 16 and 17 respectively. Figure 16 shows the average uncorrected and corrected PWI range errors for 12 runs as a function of actual horizontal range. Also shown are the upper and lower extremes comprising the limits of range error for each particular range. Since the majority of the range data resulted in a PWI range that was less than the actual radar range, the possibility existed that the initial range calibration may have changed to bias the PWI range error in this direction. The correction to the range error consisted of shifting the PWI range error ordinate so that the zero error position was equidistant between the minimum and maximum errors of the uncorrected average PWI range errors.

In assessing the PWI range accuracy as denoted in Fig. 16, consideration was given to the total range tolerances associated with the radar range and data reduction accuracies. The standard ranges for comparison with the PWI range data were obtained by timing the interval between a "mark" command from radar control at the 30-NM start range and a "mark" command from an observer as the aircraft passed the PWI ground site installation in the main building. Intermediate 1-NM range increments were based upon the average aircraft speed during the particular closing run. These range values were time-correlated with range information in the video signal and the PWI display unit. The accuracies of the radar range at the extremes of each run were estimated to be $\pm$ 0.5 NM. An additional $\pm$ 0.5 NM error was associated with the range readout from the video signal on the oscilloscope film record. A statistical combination of these errors results in a $\pm$ 0.86 mile latitude in the accuracy of the range data used as the standard for comparison purposes. Any range deviation in Fig. 16 within the $\pm$ 0.86 NM range error region was considered as within the limits of experimental error.
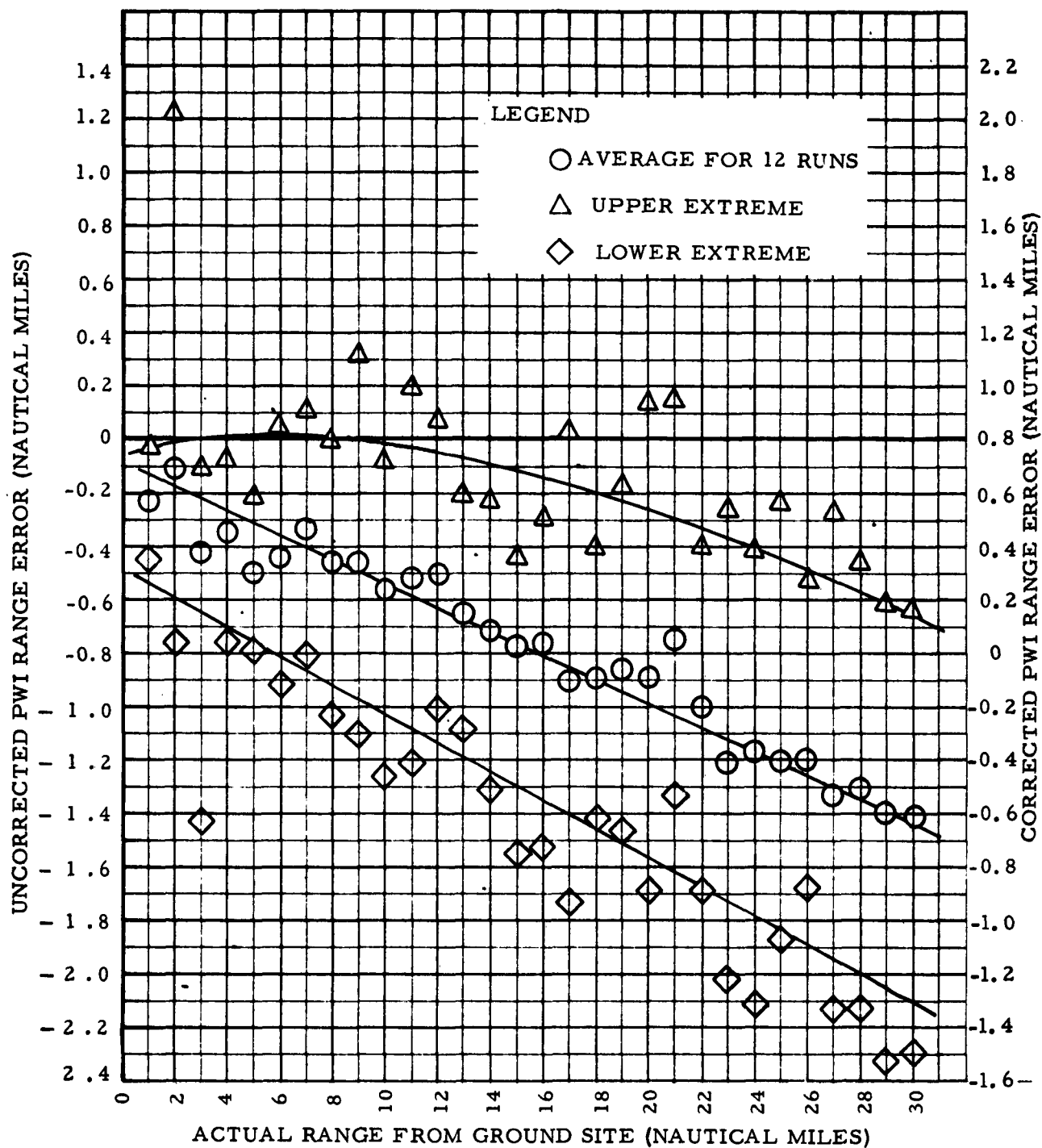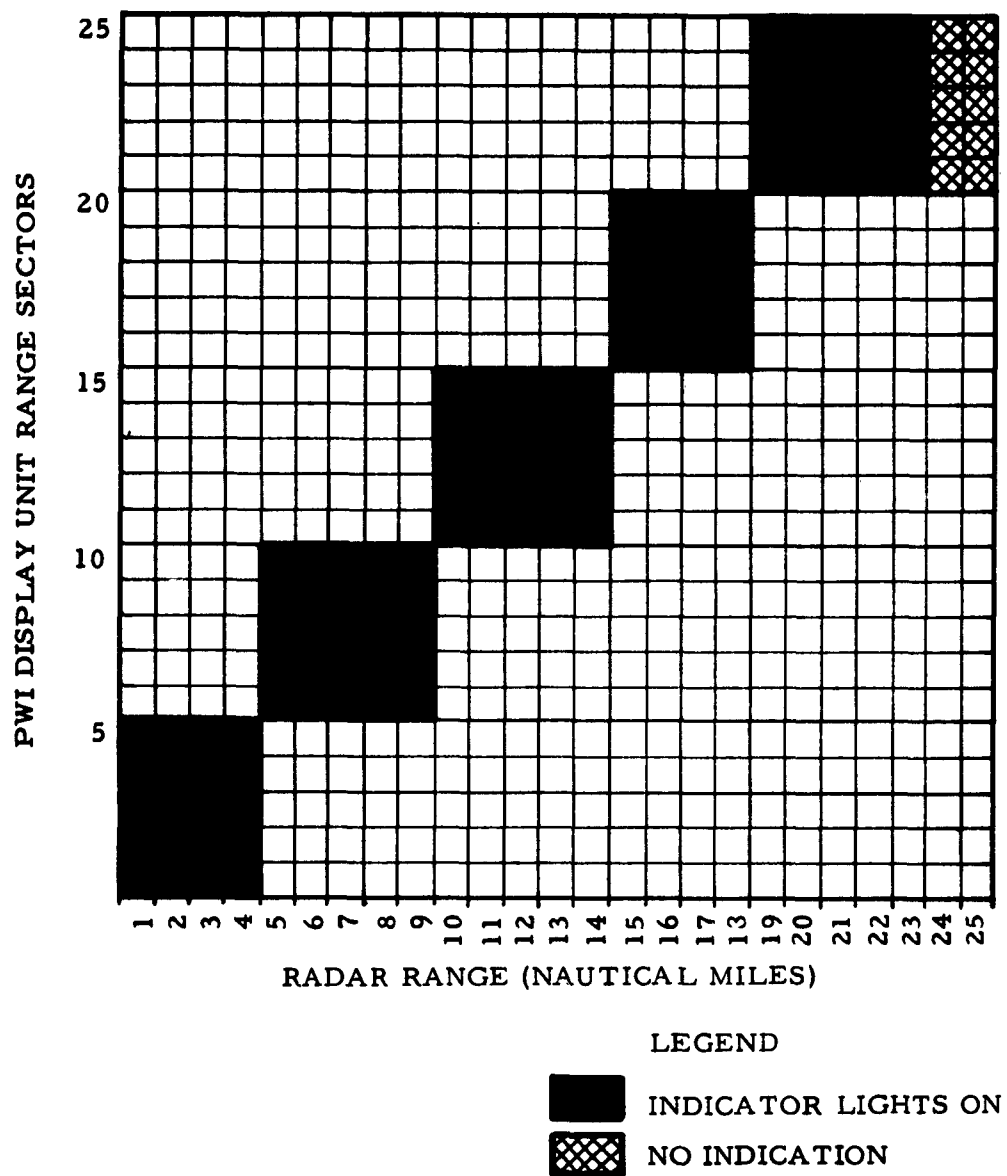
24

FIG. 16 PWI RANGE ERROR

25

FIG. 17 RANGE INFORMATION AS DEPICTED ON PWI DISPLAY
UNIT FOR A TYPICAL RUN

26

Figure 17 is a graph of the lighted PWI indicator range sectors versus the standard ranges from 0 to 25 nautical miles that were observed and recorded during a typical ground-to-air run. Based upon the standard range accuracies, the PWI display unit presentation of range information was deemed relatively accurate with the changes in range sector occurring in most instances within the $\pm$ 0.86 NM experimental range error. The average range at which the intruder position was first observed on the 20- to 25-mile sector of the PWI display unit was 24 NM. Although the range presentation was electronically limited to a maximum of 25 NM, the 30-NM start range for the 12 runs was well within the threshold range of the PWI communication link, since in all cases range information was noted on the oscilloscope traces of the video signal.

5. Effects of Interference on PWI Performance: For the air-to-air test to determine the effects of self-generated interference on PWI performance, a complete PWI system and photopanel were installed in each of two C-45 type NAFEC aircraft. The photopanel, with camera attached, contained the PWI display unit; remote instruments of aircraft roll, pitch, heading, airspeed, altitude, and outside air temperature; and a clock and counter for data correlation purposes. (The PWI antenna installation on the project aircraft is shown in Fig. 1.) The PWI and instrumentation installation in the project aircraft is shown in Figs. 18 and 19.

The tests were conducted over water and land with the aircraft under radar control and surveillance. A series of forward hemisphere-to-forward hemisphere collision courses were flown with the relative position of the intruder aircraft varying from 090° to 270°. Each run started with a 30 NM separation between aircraft.

The display unit in each aircraft was constantly observed during the tests. Photographs of one display unit were taken at approximately 1-second intervals during closure to provide a record of the PWI display and aircraft performance characteristics for future data reduction and analysis. In addition, the PWI video signal, which denotes range by the elapsed time between signal interrogation and reception, and indicates intruder aircraft relative bearing by the amplitude and sign of the video pulse, was monitored on an oscilloscope in one of the project aircraft.

The runs associated with the first over-water flight were made with both aircraft operating at a 6000-foot altitude. During these runs, the PWI display unit range and bearing information was confusing due to the presence of false fluctuating signals that prevented the positive identification of the true target. Observations of the video signal on the airborne oscilloscope
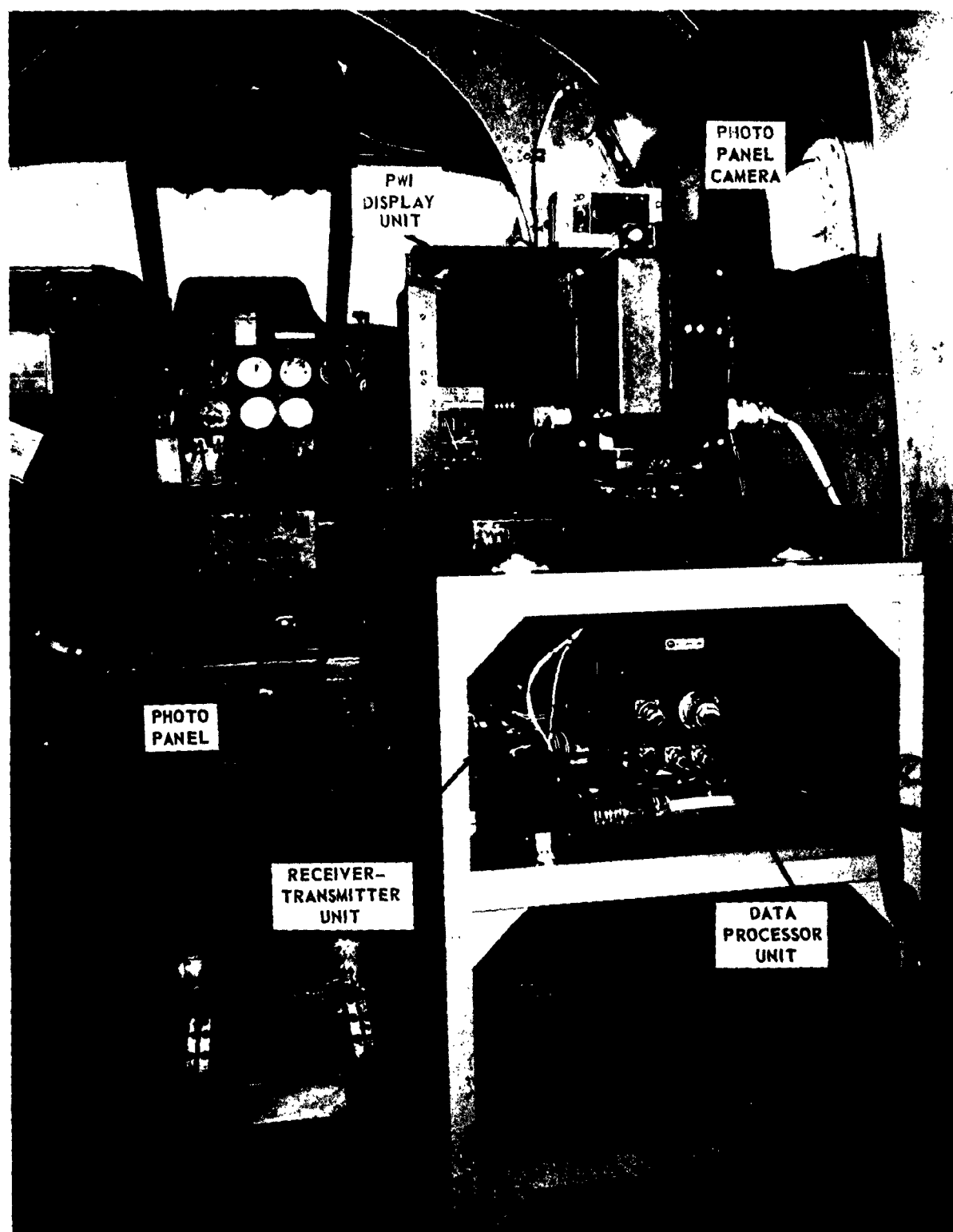
27

FIG. 18 EQUIPMENT ARRANGEMENT IN PROJECT AIRCRAFT
FOR AIR-TO-AIR TESTS

28

PHOTO
PANEL
CAMERA

PWI
DISPLAY
UNIT

DATA
PROCESSOR

PHOTO
PANEL

RECEIVER-
TRANSMITTER UNIT

FIG. 19 CLOSE-UP OF EQUIPMENT ARRANGEMENT IN PROJECT
AIRCRAFT

revealed that the amplitude of the video pulse was varying in a cyclic manner and was in synchronism with the display unit target fluctuations. Since the target relative bearing was determined by the amplitude of the video pulse, it was obvious that the fluctuating display lights indicating target bearing were caused by the oscillatory rise and decay of the video signal. In addition, range variations noted on the PWI display unit were attributable to horizontal jitter of the video pulse that altered the time duration between the initiating interrogation and the received signal. Since range was based upon this time relationship, changes in the time period produced range variations on the PWI display unit. Two additional over-water flights produced the same confusing results. However, as the operating altitude of the aircraft decreased, the frequency and amplitude of the cyclic video signal variations were reduced.

In flights over land, the occurrence of false target signals on the PWI display unit increased, but no repetition period could be established. The intruder aircraft position information on both the display unit and the oscilloscope trace was erroneous and erratic. The degree of display confusion was dependent upon the same altitude factor previously described.

It was concluded from a study of the PWI display unit presentation problem that the interfering signals were being received at the project equipment by either a ground-reflected path or by reflections from the carrying aircraft structure. A special ground-to-air test was conducted to determine which of these possible interfering sources was causing the erratic PWI operation. With one complete PWI system mounted atop a NAFEC laboratory building approximately 10 feet above the ground and another installed in the project aircraft, a series of runs were flown over the PWI ground site at an altitude of 3000 feet. Each run started from 30 miles and was concluded when the incoming aircraft closed to zero horizontal range or executed a slow turn that caused the airborne display unit presentation of the ground-site position to move from dead ahead to either the 60° -90° left sector or 60° -90° right sector. During this test, the effects of ground-reflected signals were minimized, since one system in the PWI communications link was located near ground level and the differences in path lengths between the direct path transmissions and any reflected path transmissions were negligible. With the ground-reflection problem considerably reduced by this PWI communication link, any erratic PWI signal behavior on the airborne display unit would be attributable to reflections from the carrying aircraft. As observed, the target indications on the PWI display unit and the monitoring oscilloscope in the project aircraft were clear and consistent, with the PWI range and bearing sector lights indicating proper segmented position information relative to the location of the ground site.

In Fig. 20, examples of the confusing PWI range and bearing indications received during the air-to-air tests are compared with the PWI target display information obtained during the air-to-ground tests. Unfortunately, the photographic evidence of system performance was not in a form capable of direct reproduction. The illustrations in Fig. 20 were extracted from the photographic record and represent consecutive data-gathering frames at approximately a 1-per-second rate. Figure 20A, B and C are comparisons of the air-to-air and ground-to-air display information. Figure 20D is an illustration of 10 consecutive frames of PWI display unit data collected during the air-to-air tests to denote the degree of PWI display confusion. For this particular run, the 30° -60° right bearing sector in the 20-25 NM range sector should be lit. All other target indications are false.

The results of these tests revealed that the major contributing factor to the interference problem was the presence of a PWI ground-reflected signal in addition to the desired direct-path signal. When the ground-reflected signal was minimized, the video and PWI display unit signals were more easily interpreted.

The behavior of the propagated signal from the PWI aircraft and the interfering effects of ground-reflected signals on the direct signal were in agreement with the theory and experimental verification of the theory.[3] In regard to the oscillatory nature of the PWI video signal when flying over water and the absence of a well-defined repetitive period when flying over flat land, Reed and Russell state, "For propagation over smooth water or over obstruction-free flat land a single earth reflected ray, only, has been assumed to exist and that such an assumption is justified has been shown by the close correlation between theoretical interference patterns and experimental data. With propagation over a rough surface, multipath reflection occurs, and the resultant interference pattern is no longer that predicted by the two-path theory.[4] Concerning air-to-air propagation experiments conducted over water and flat land, Reed and Russell further state, "The signal strength recording for the over sea water flight shows a well-defined interference pattern. The over smooth land recording again shows a definite interference pattern, but the variations are irregular. Departures from the interference pattern predicted by two-path theory for
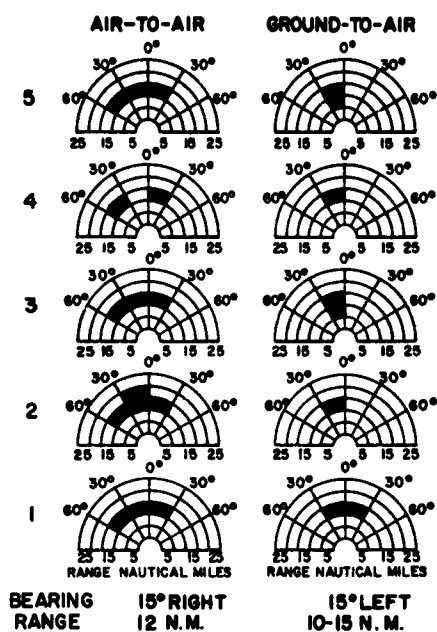
[3]Reed and Russell, "Ultra High Frequency Propagation," John Wiley and Sons, New York, 1953, Chapter 10.
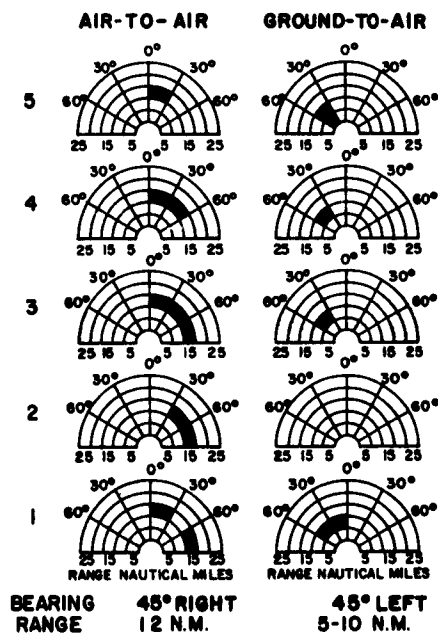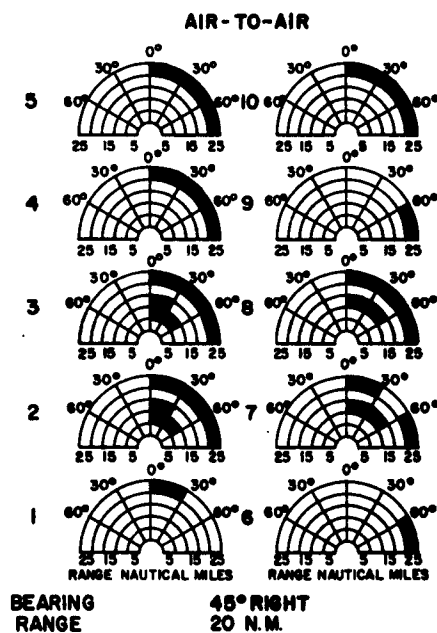
[4]Reed and Russell, op. cit., pp. 397-399.
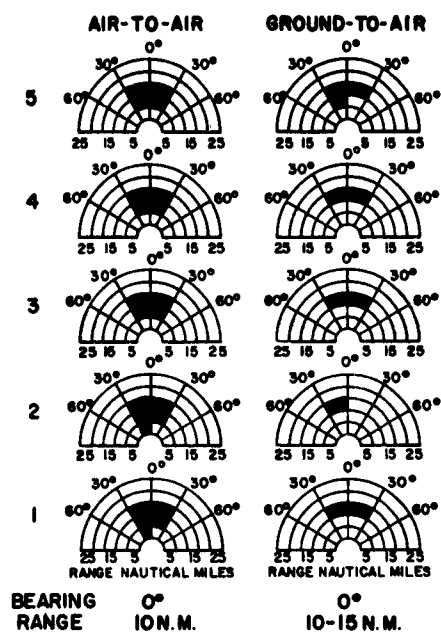
FIG. 20   COMPARISON OF PWI DISPLAY UNIT PRESENTATIONS
FROM AIR-TO-AIR AND GROUND-TO-AIR TESTS

a smooth land reflecting surface can be attributed in a large part to the finite roughness which existed at the site of the test." The reduction in the frequency and amplitude of the cyclic video signals as the operating altitude of the PWI aircraft decreased also agreed with theoretical predictions of the interference modulation frequency as a function of operating altitude. [5]

   6.   Canceled Air-to-Air Tests: Air-to air tests to obtain usable data for the determination of the PWI communication volume coverage and the enhancement of a pilot's discerning capability when provided with PWI information were canceled due to the compromising effects of ground-reflected interference on the PWI performance.

Summary of Results

   1.   The altitude acceptance band of the PWI increased with operating altitude. At a 20,000 foot altitude, the PWI altitude acceptance band was 13,000 feet.

   2.   Based upon the average, the range accuracy of the PWI was within the $\pm$ 0.86 NM experimental error of the instrumentation and technique used for the range measurement.

   3.   Within the forward hemisphere coverage of the PWI, the bearing error increased with relative bearing angle to a maximum of 28° at or near the 090° and 270° positions.

   4.   During the air-to-air tests, ground-reflected interference signals generated by the PWI furnished erroneous and erratic intruder aircraft position information to the PWI display unit.

   5.   Equipment performance prevented accomplishment of that part of the project aimed at determining the utility of pilot warning information as an aid to collision prevention.

[5]Reed and Russell, op. cit., pp. 380-382.

I

CONCLUSIONS

The following conclusions are based upon an analysis of the observed and/or recorded evaluation results:

1. Although the desired altitude acceptance band has not been specified, the band that exists is considered to be excessively wide. The acceptance band can be made smaller by redesign.

2. The range accuracy of the PWI was considered adequate for the particular application.

3. The bearing error of the PWI was considered excessive for the particular application. These errors are inherent in the method of relative bearing determination.

4. Self-generated, ground-reflected interference signals seriously degraded the PWI performance. These effects result from characteristics of this technique that are not easily overcome.

5. The PWI technique used in the project equipment is not considered reliable for pilot use as an aid for airborne collision prevention.

6. No conclusion can be drawn from this work as to the utility of pilot warning information as an aid in collision prevention.

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RECOMMENDATIONS

It is recommended that:

1. The phase comparison method of determining relative bearing used in this equipment should not be adopted.

2. Alternate electronic and/or optical techniques for improving a pilot's discerning capability be investigated for possible utility as a PWI.

ACKNOWLEDGMENT

36

APPENDIX I

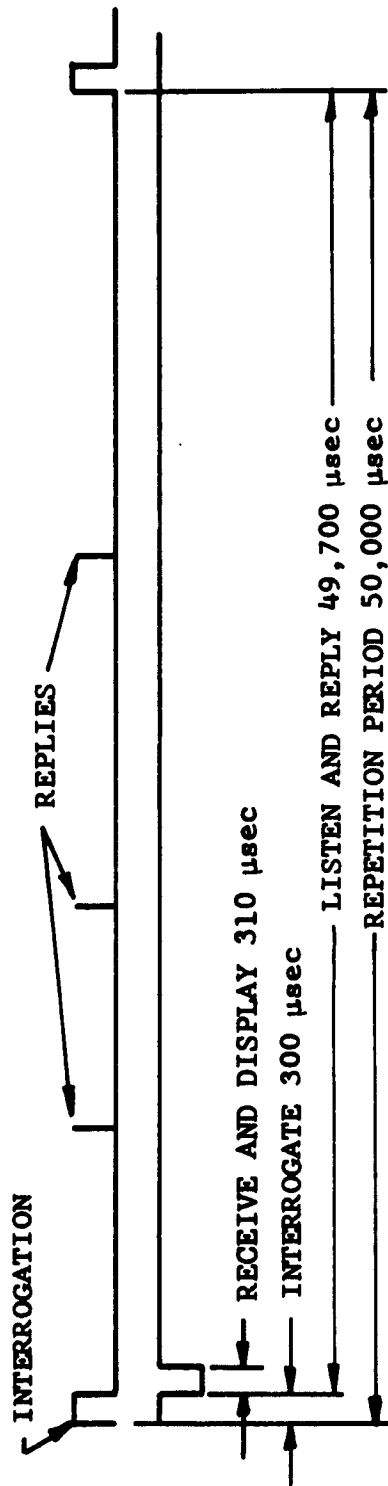## PILOT WARNING INSTRUMENT THEORY OF OPERATION

General

The Pilot Warning Instrument (PWI) is a system that requires equipment in each cooperating aircraft. For this discussion, the PWI theory of operation will be limited to the PWI performance in one aircraft. This description is typical for all PWI-equipped aircraft.

The receiver-transmitter (R-T) unit receives and transmits in a programmed manner. The transmission and receiving sequence is shown in Fig. 1. The basic PWI repetition rate is 20 cycles per second (cps) or 50,000 microseconds (μsec) per one full cycle. In the interrogating mode, the transmitter produces an interrogation pulse during the first 300 μsec of the cycle. For the remaining 49,700 μsec of the cycle, the PWI is in the receiving and transponding mode. If a reply to the PWI interrogation is received during the 310-μsec period following the interrogation, an indication is displayed to the pilot. The PWI display maximum range is limited to 25 nautical miles, which is 310 μsec based upon 1 radar mile equal to a 12.4-μsec delay. Replies received after this 310-μsec interval will be beyond the 25-NM range and will not be displayed.
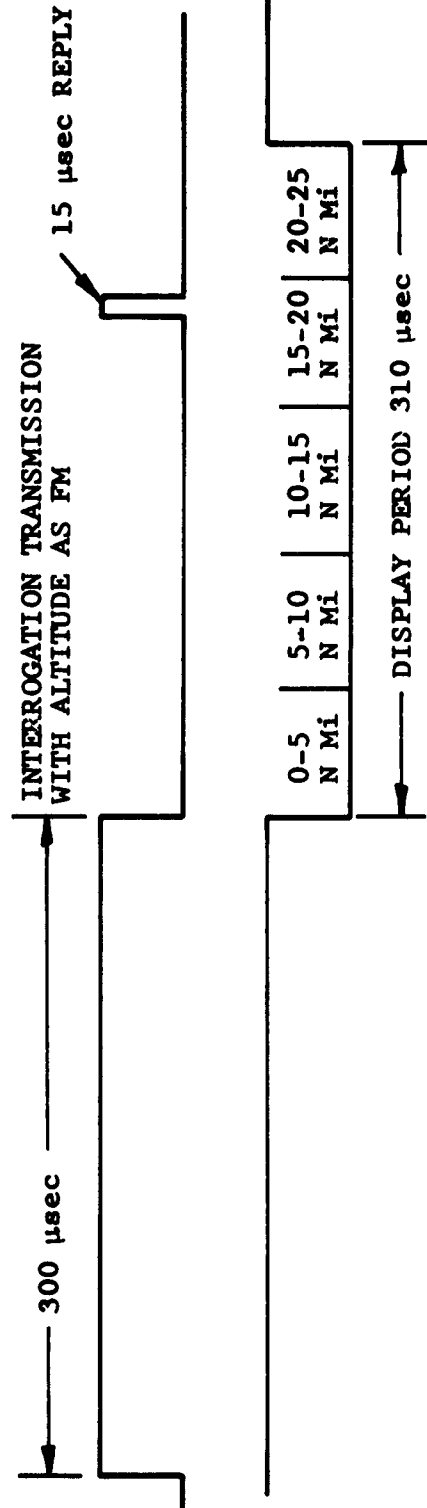
Receiver-Transmitter Unit

The R-T unit is the interrogation and data collection unit of the PWI. The functional diagram of the receiver-transmitter unit and the barometric coder-decoder unit is shown in Fig. 2.

1. **Transmitter Section:** The 20-cycle multivibrator (MV) generates the signals to establish the basic 20-cps repetition rate of the PWI. The output of the 20-cycle MV triggers the 300-μsec MV long-pulse stage which provides the interrogation pulses for the operation of the modulator and transmitter stages. The transmitter output is connected to the transmitter antenna. During the interrogation pulse, the modulator is gated on to allow transmission of the altitude code signal from the barometric coder-decoder unit. In addition, the trailing edge of the 300-μsec MV long-pulse stage starts the range sweep in the data processor unit and triggers the inhibitor stage. The inhibitor stage furnishes a pulse to form a narrow inhibit gate that

INTERROGATION

REPLIES

RECEIVE AND DISPLAY 310 μsec
INTERROGATE 300 μsec
LISTEN AND REPLY 49,700 μsec
REPETITION PERIOD 50,000 μsec

A. - COMPLETE PWI CYCLE

INTERROGATION TRANSMISSION WITH ALTITUDE AS FM

15 μsec REPLY

300 μsec

| 0-5 N Mi | 5-10 N Mi | 10-15 N Mi | 15-20 N Mi | 20-25 N Mi |

DISPLAY PERIOD 310 μsec

B. - ENLARGEMENT OF FIRST 610 MICROSECONDS OF PWI CYCLE

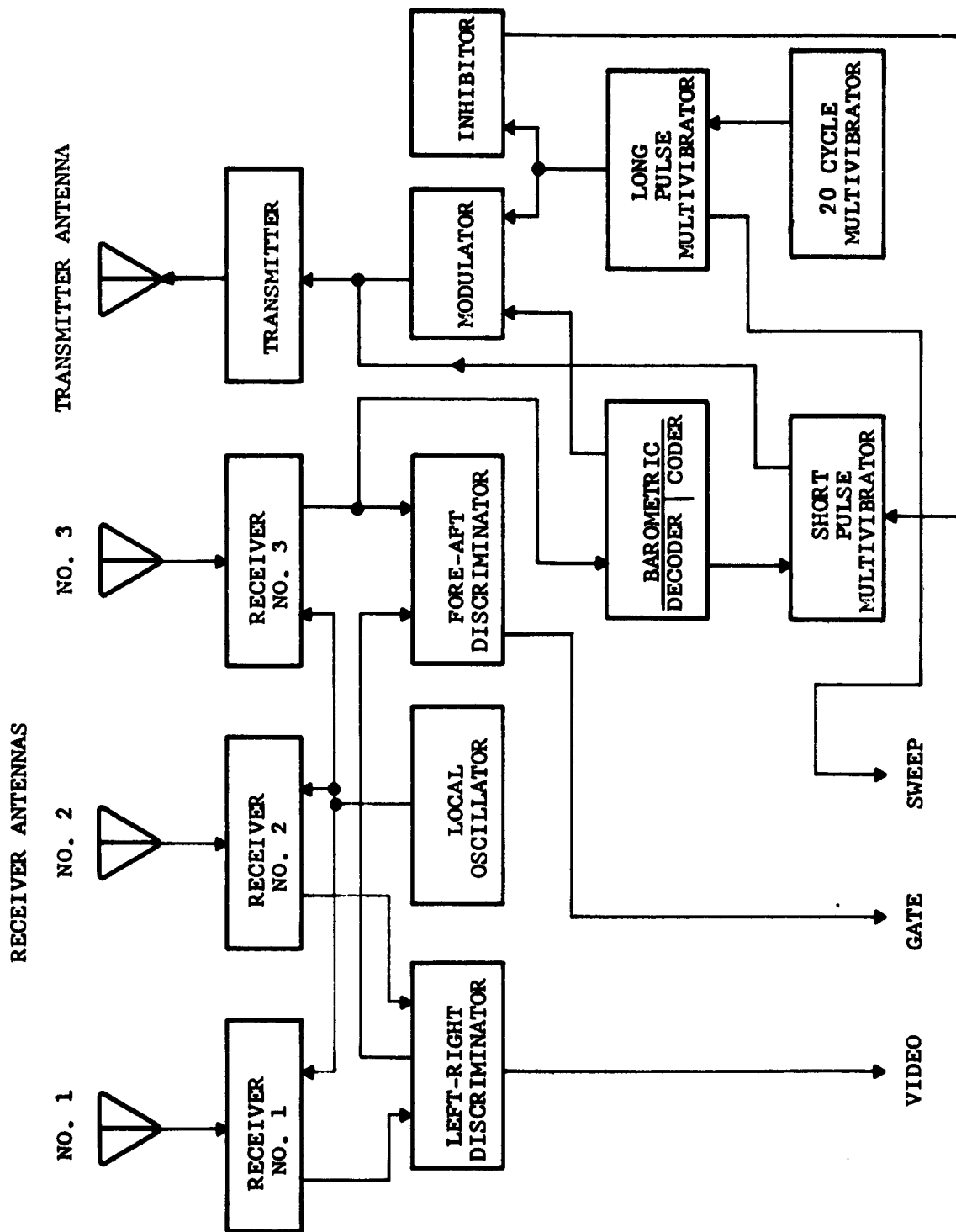FIG. 1 PWI RECEIVER-TRANSMITTER TIME-SHARING SEQUENCE

FIG. 2 FUNCTIONAL DIAGRAM OF PWI RECEIVER-TRANSMITTER
UNIT WITH BAROMETRIC CODER-DECODER UNIT

prevents the PWI from replying to self-generated interrogations. At the end of the inhibit gate signal, the system is in the listening mode preparatory to the receipt of interrogation or reply signals from other PWI-equipped aircraft.

2. Receiver Section: The PWI receiver processes signals from interrogations and replies from other PWI-equipped aircraft. These signals are received on antennas 1, 2, and 3. Antennas 1 and 2 are identified as the units mounted transverse to the aircraft flight line. Antenna 3 is identified as the unit located behind and perpendicular to antennas 1 and 2. The relative bearing of the cooperating aircraft is determined by measuring the phase difference of arrival of the wavefront at the two forward antennas. Range is determined by measuring the time delay from the end of an interrogation to receipt of the corresponding reply signal. Each numbered receiving antenna is connected to a correspondingly identified receiving stage. The receivers are identical in design and are double-conversion, super-heterodyne types. The local oscillator stage is common to all the receivers to establish a reference phase relationship in the receivers. The outputs of receiver stages 1 and 2 are connected to the left-right discriminator stage that measures the received signal phase and range parameters, and furnishes this information in the form of a video signal to the data processor unit. The video signal amplitude is a sinusoidal function of the angle of arrival of the received signal. In addition, a reference signal from these receivers is fed to the fore-aft discriminator stage. The output of receiver stage 3 is also connected to the fore-aft discriminator stage. With these two inputs, a measurement is made to determine whether the received signal wavefront arrived from the forward or rear relative azimuth sector of the aircraft. Since only forward sector received signals are displayed, the determination of a forward sector signal by the fore-aft discriminator produces a 15-μsec gate-on pulse to the data processor unit. Typical oscilloscope traces of the video and gate signals are shown in Fig. 3. The video signal is the upper trace. Another output of receiver stage 3 is connected to the barometric coder-decoder unit to furnish the received signal sample for establishing coincidence with the altitude-coded interrogation signal prior to initiating the 15-μsec MV reply transmission.
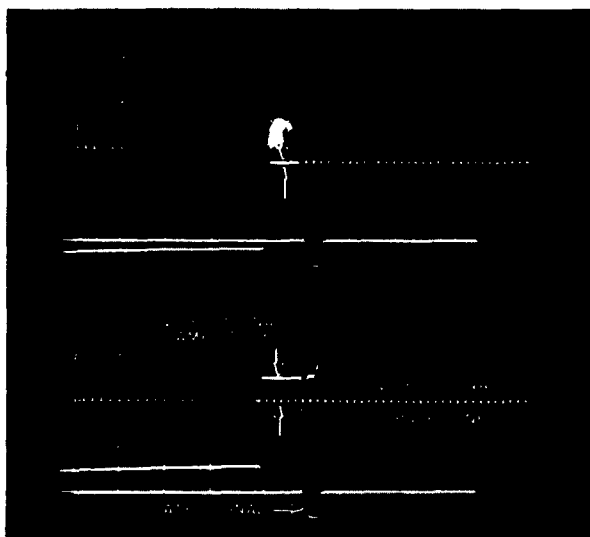
Barometric Coder-Decoder Unit

The barometric coder-decoder unit provides the altitude discrimination feature to the PWI by completing the communications
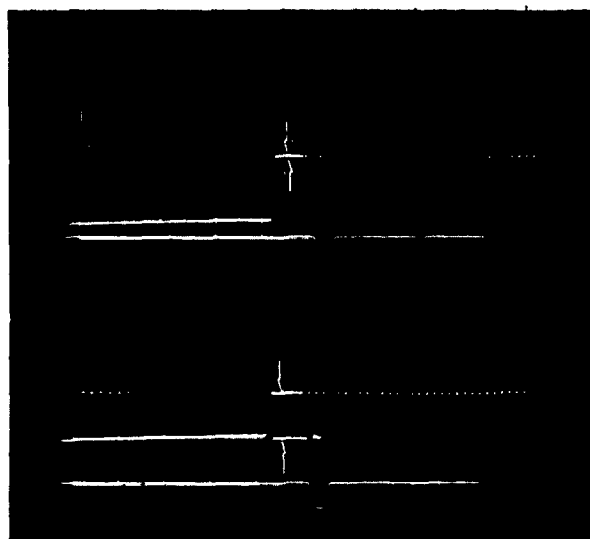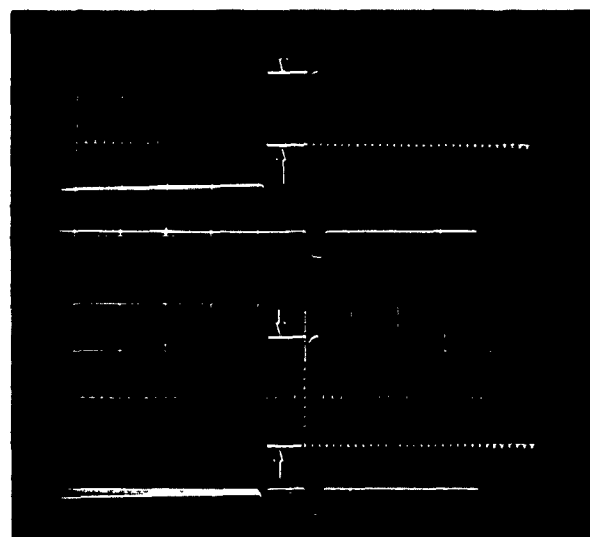
0°
30° LEFT
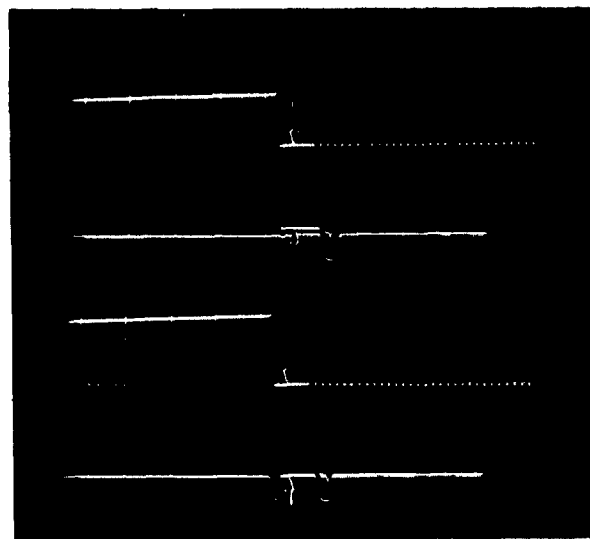
60° LEFT
90° LEFT

0°
30° RIGHT

60° RIGHT
90° RIGHT

TIME BASE - 50M SEC/CM
VERTICAL SENSITIVITY - 0.5 VOLTS/CM

FIG. 3   PWI VIDEO AND GATE SIGNALS

link only when the aircraft are operating at or near the same altitude. This is accomplished by FM coding the transmitter and receiver as a function of pressure altitude. Both the oscillator-tuned circuit for the transmitter and the filter-tuned circuit for the receiver in the barometric coder-decoder unit are mechanically connected to a sealed bellows attached to the aircraft static pressure line. The oscillator-tuned circuit output phase modulates the modulator during interrogation, the modulation frequency being dependent upon the operating altitude. The tuned-filter circuit output controls the PWI reply to interrogations from other PWI-equipped aircraft by providing initiating pulses to the 15-μsec MV short-pulse stage only when the altitude-coded interrogation and received signals in the barometric coder-decoder unit are coincident. The output of the 15-μsec MV short-pulse stage keys the transmitter stage for a 15-μsec reply transmission.

Data Processor Unit

The data processor unit consists of five main sections: the discriminator amplifier, left-right logic, Schmitt trigger, "AND" gate, and range multivibrator sections. Figure 4 is a block diagram of the various stages and substages comprising the data processor unit.

1. Discriminator Amplifier Section: The discriminator amplifier section consists of five basic subsections: The video signal from the R-T unit is applied to the right and left discriminator amplifiers, the positive or right video information to the right discriminator amplifier, and the negative or left video information to the left discriminator amplifier. Since the output signals from these amplifiers must be negative for further processing, the positive or right video signal is also inverted in the right discriminator amplifier. The 15-μsec gate signal is fed to the biased saturated amplifier which furnishes a near constant output pulse only when a gate signal is available. When an output signal is generated in the biased saturated amplifier, it opens the two normally closed gate subsections for the time interval corresponding to the gate signal. Since both video and gate signals are initially produced by the same received 15-μsec signal at the PWI antennas, a coincidence of the video and gate information is established. Opening the normally closed gates in coincidence with the outputs from the right and left discriminator amplifiers squelches the noise and limits the outputs of these amplifiers to only the video pulse interval, thus minimizing the PWI response to spurious interference.
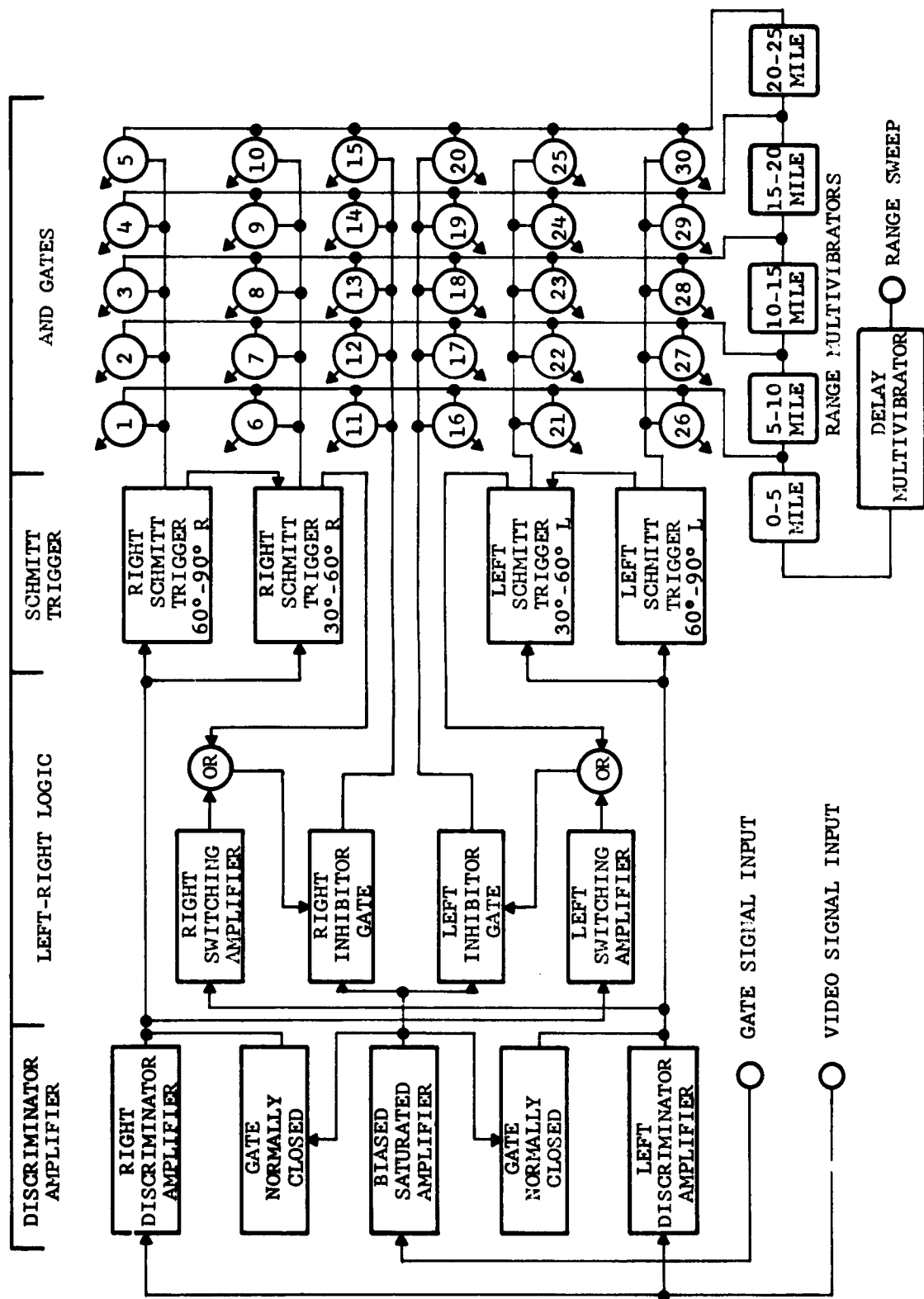
FIG. 4 FUNCTIONAL DIAGRAM OF PWI DATA PROCESSOR UNIT

When no gate signal is available to the data processor unit, as in the case of the relative position of the received signal source being in the rear sector of the PWI aircraft, no coincidence between the normally closed gates and the right and left discriminator amplifiers can be established, since there is no output signal from the biased saturated amplifier to open the normally closed gates. For this situation no range or bearing information is displayed.

2. <u>Schmitt Trigger Section</u>: The video and fore-aft gate outputs from the discriminator amplifier section are connected to the Schmitt trigger and right-left logic sections. For the sake of simplifying the description, only the right sector signal circuits are discussed. These functions are also typical for the left sector. The two right sector Schmitt triggers are used to convert an analogue pulse voltage whose amplitude represents angle into a digital pulse in the proper channel to represent an angular increment. The two right Schmitt triggers are biased so that they do not fire until analogue outputs from the right discriminator correspond to angles within the Schmitt trigger acceptance bands. A pulse of sufficient amplitude to trigger the 30°-60° R Schmitt stage produces a negative pulse output from this Schmitt trigger that is fed to AND gates 6 to 10, inclusive, in the AND gate section. When the amplitude of the pulse from the right discriminator amplifier corresponds to an angle between 60° and 90°, the 60°-90° R Schmitt trigger negative output pulse is concurrently applied to the 30°-60° R Schmitt trigger and AND gates 1 to 5, inclusive, in the AND gate section. This negative pulse into the 30°-60° R Schmitt trigger prevents triggering of the 6 to 10, inclusive, AND gates.

3. <u>Left-Right Logic Section</u>: Since the bearing information is dependent upon the amplitude of the pulse from the right discriminator amplifier, cooperating aircraft relative bearings at or near 000° provide low-amplitude signals that are not reliable for display. To overcome this unreliability, the fore-aft pulse from the biased saturated amplifier is applied to the right-left logic section. For the 000° relative bearing display, the biased saturated amplifier output is fed to both inhibitor gates, resulting in the triggering of AND gates 11 to 20, inclusive. As the relative position of the cooperating aircraft moves from 000° to the right, the left switching amplifier produces an output which passes through the left "OR" gate to block the fore-aft pulse through the left inhibit gate, thus preventing the firing of AND gates 16 to 20, inclusive, while allowing AND gates 11 to 15, inclusive, to be energized. As the relative position of the cooperating aircraft exceeds 030°, the output from the 30°-60° R Schmitt trigger is applied through the right OR gate to inhibit the

fore-aft pulse through the right inhibit gate, preventing AND gates 11 to 15, inclusive, from being energized by the right inhibit gate pulse. As previously described, the display inputs for bearings in excess of 30° to the right are provided by outputs from the right discriminator amplifier and 30°-60° R and 60°-90° R Schmitt triggers.

4. Range Multivibrator Section: The range multivibrator section consists of five multivibrators which are sequentially triggered every 62 μsec of the 310-μsec display time. Each of the multivibrators represents 5-mile increments in range from 0 to 25 nautical miles. The input to start the ranging sequence is provided by the range sweep signal generated in the R-T unit following the interrogation pulse. The output from each of the five multivibrators is applied to the appropriate AND gate. The delay multivibrator compensates the displayed range information for delays inherent in the system.

5. AND Gate Section: The AND gate section consists of 30 gates that process azimuth input information from the Schmitt triggers and inhibitor gates, and range input information from the range multivibrators. Range and bearing sectors of the AND gates are fully energized whenever a coincidence of these two inputs exists. Each AND gate is followed by a 20-millisecond multivibrator that provides an output pulse of sufficient duration and amplitude to fire the appropriate light in the PWI display unit.

Display Unit

The PWI display unit is shown in Fig. 5. The unit consists of a display that provides forward azimuth information in six equal 30° sectors, and range information in five equal range sectors to 25 nautical miles for a total of 30 segments. Each segment is illuminated by a lamp that is energized by a pulse from the related active AND gate.
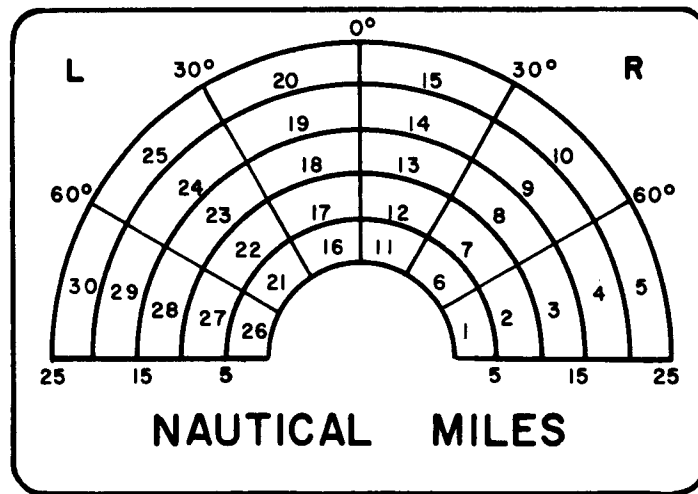
FIG. 5 PWI DISPLAY UNIT