DEVELOPMENT OF A VARIABLE-PARAMETER DME INTERROGATOR

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SUMMARY

This report describes the development of a test unit designed to permit airborne checking of the performance, coverage, system interference, and multipath transmission of the DME transponder The unit has been designated as a Variable-Parameter DME Interrogator (VPDI) A description is given of the modifications made to an early-model conventional interrogator to render it capable of performing the functions desired of the VPDI The characteristics of the VPDI are outlined, and the results of the initial flight tests are described

INTRODUCTION

Determination of the maximum range capability of distance-measuring-equipment (DME) systems has long been a problem surrounded by variables [1] Attempts to predict coverage statistically are relatively meaningless because of the differences between the free-space patterns and the wide variation of antenna patterns encountered operationally Transponder antennas are essentially standardized, however, their effective patterns vary greatly from site to site The patterns of aircraft antenna vary with the type of aircraft, the antenna location, and the antenna design The fact that the DME system involves a two-way transmission further complicates the problem The conventional interrogator provides only a "go-no go" indication of system performance and when failing in indication does not provide the means for determining the limiting parameter The following parameters are of significance in determining whether a signal of the proper form to operate the ranging circuits of a conventional interrogator will appear at the output of the interrogator decoding circuits

1 Power output of interrogator transmitter
2 Frequency of interrogator transmitter
3 Code-spacing of transmitted pulse pair
4 Receiver sensitivity of DME transponder
5 Frequency to which the transponder receiver is tuned
6 Decode-spacing of transponder
7 Code-spacing of transponder reply
8 Power output of transponder transmitter
9 Frequency of transponder transmitter
10 Sensitivity of interrogator receiver
11 Frequency to which interrogator receiver is tuned
12 Decode spacing of interrogator receiver

The dependence of the distance indication on these characteristics is shown in Fig 1

The equivalent parameters of the companion equipment to the DME in the rho/theta short-range navigation system, the very-high-frequency (VHF) omnidirectional range (VOR),[2] a one-way transmission system, are

1 Power output of ground VOR transmitter
2 Frequency of ground VOR transmitter
3 Sensitivity of airborne VOR receiver
4 Frequency to which airborne VOR receiver is tuned

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*Manuscript submitted for publication September 1953

[1] R C Borden, C C Trout, and E C Williams, "UHF Distance Measuring Equipment for Air Navigation," CAA Technical Development Report No 114, June 1950

[2] H C Hurley, S R Anderson, and H F Keary, "The CAA VHF Omnirange," CAA Technical Development Report No 113, June 1950

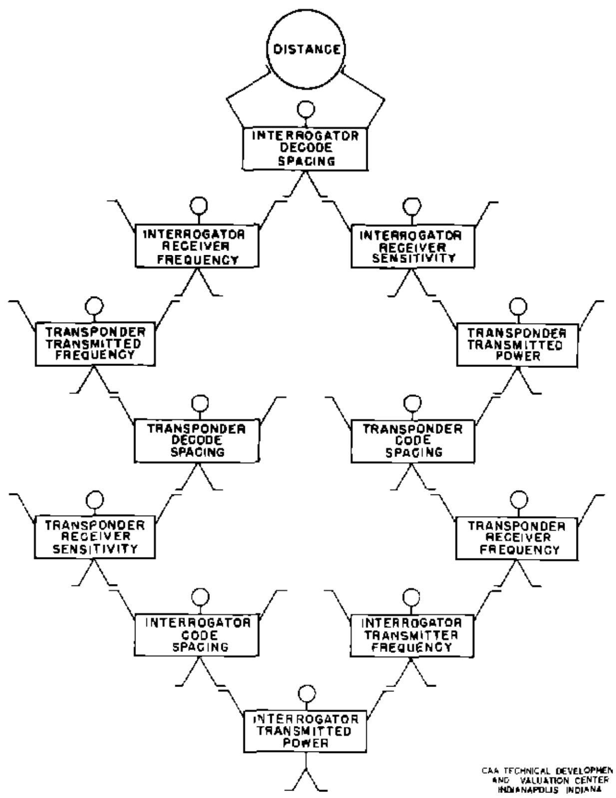


Fig. 1 Dependence of Distance Indication on System Variables

In the case of either the VOR or the DME, the proper adjustment of the listed variables does not guarantee accuracy of indication but simply insures reception of the optimum signal amplitude.

The problem of flight-checking a VOR ground station differs in two respects from that of flight-checking a DME transponder. These respects are

1. VOR receivers containing crystal-controlled local oscillators are at present available and thus virtually assure frequency compatibility, because the VOR transmitter is also crystal-controlled. On the other hand, not all interrogator and transponder transmitters now in use are crystal-controlled
2. The siting of the VOR transmitter is a significant factor in the determination of the azimuth accuracy as well as in the determination of the coverage of the VOR station, whereas the siting of the DME transponder affects the DME coverage but not its accuracy.

Hundreds of hours of flight-checking with the present and earlier DME systems at the Technical Development and Evaluation Center of the Civil Aeronautics Administration have repeatedly shown that accurate coverage-pattern recording is virtually impossible because of inadequate control of the 12 variables previously enumerated.

To insure that the complete system is at optimum performance during the course of such measurements, the VPDI was designed. When the VPDI is used with an oscilloscope, compatibility of frequency and of code-space links can be ensured. The signal strength available at the receiver, together with the distance, can then be measured and recorded. In order to provide this flexibility, the following parameters of the VPDI are made manually and independently variable

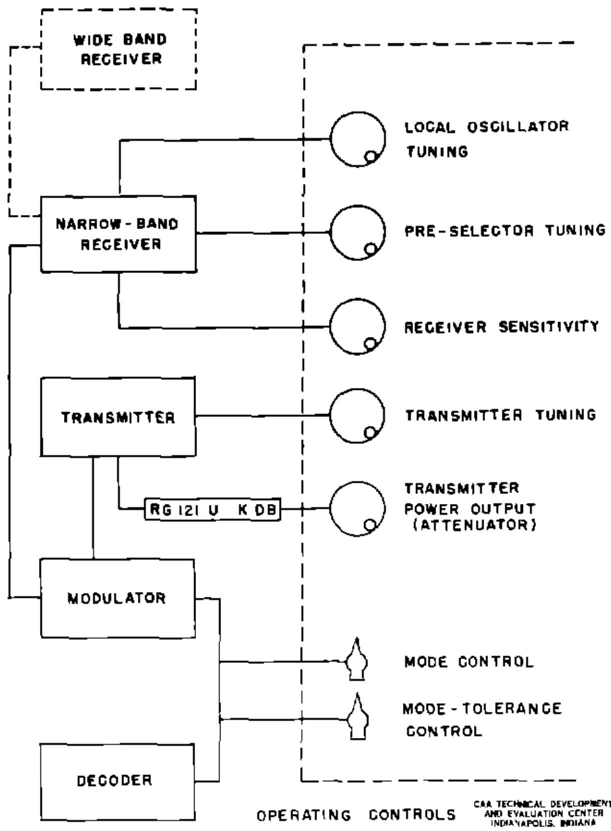


Fig 2 Block Diagram of VPDI Showing Operating Controls

1. Power output
2. Receiver sensitivity
3 Transmitter frequency
4 Receiver frequency
5 Transmitted pulse-pair spacing (mode).
6 Decode spacing (mode)

Figure 2 is a block diagram of the VPDI and illustrates the controlled functions

For purposes of coverage determination, absolute accuracy of the frequency and code-space links is not important, provided that the airborne variables are at the optimum point in relation to their companion variables at the transponder Where it is desired to measure the characteristics of a ground station, the VPDI variables after optimum adjustment may be measured in flight by the use of available test equipment These measurements apply to the companion parameters of the ground station.

DESCRIPTION OF MODIFICATIONS

When the requirements of the VPDI and the characteristics of the interrogators available for modification were considered, the Hazeltine Electronics Corporation Model 1355 DME 50-channel interrogator was selected as the basis for the VPDI The following features of the Model 1355 governed this choice

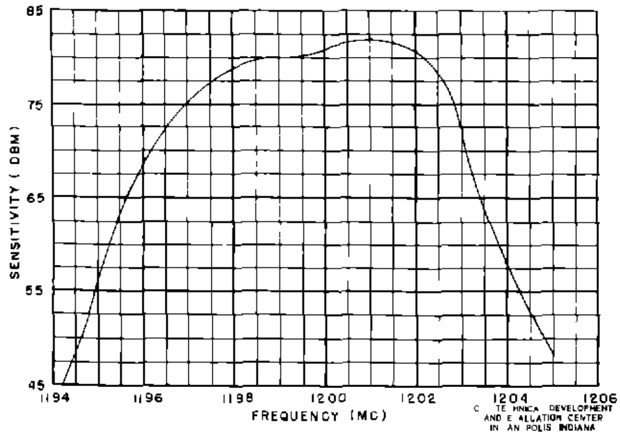


Fig 3 Receiver Response Curve (Wide Intermediate-Frequency)

1. The tuning range of the radio-frequency cavities are more than adequate for application as VPDI.
2. The power-output and the receiver-sensitivity characteristics are suitable.
3. Both the transmitter and the local oscillator are self-excited.
4. There is sufficient equipment available to provide spare parts for the VPDI.
5. Various mechanical factors are favorable.

Radio-Frequency Head.

Much modification of the radio-frequency head was necessary to accomplish three primary objectives. These objectives were (1) to provide separate and entirely independent cavities for the transmitting and receiving functions, (2) to make the transmitter frequency continuously variable throughout the airborne-transmitter band, and (3) to make the local oscillator and the preselector of the receiver continuously variable throughout the airborne-receiver band.

In accomplishing these objectives, the power output of the transmitter and the sensitivity of the receiver should not be deteriorated. Even though the transmitter has a separate antenna and cavity, a T/R tube is needed because of the close proximity of the two antennas on the airplane fuselage.

To isolate the transmitter and receiver cavities in the radio-frequency head, a thin copper partition was installed between them. The copper wall was soldered in place and was curved so that it would clear the preselector tuning plunger. Measurements made before and after the modification indicated no change in maximum power output. The purpose of isolating the two cavities was to permit adjustment of the output power of the transmitter through use of external v-f attenuating cable without affecting the receiver sensitivity The transmitter design prohibits adjustment of the power output through the control of operating voltages

The next step was to inject the received signals into the preselector. A hole was cut in the cavity concentric with the T/R tube, and a Type BNC connector which terminated in an electrostatic probe adjusted for critical coupling was inserted. Measurements of the sensitivity before and after the installation of the receiver probe showed no deterioration. A separate control was provided for the preselector tuning, and a calibrated dial with a vernier was attached to allow the preselector to be preset accurately. A stop was provided to prevent the preselector plungers from damaging the receiver probe.

Provision for the continuous tuning of the transmitter and local-oscillator cavities was incorporated by the removal of the original tuning drum of the Model 1355 interrogator with its discrete steps or detents and by the substitution of a tuning drum with a smooth inclined plane. The rise of the inclined plane was made sufficent to cover the respective frequency ranges with adequate overlap. Separate tuning shafts were brought out to the front of the radio-frequency head, and tuning knobs and indicators were added to facilitate the adjustment and positioning of the cavity plungers.

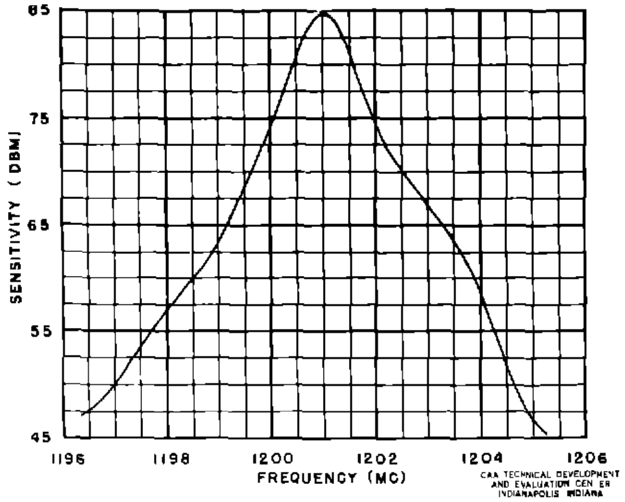


Fig 4 Receiver Response Curve (Narrow Intermediate Frequency)

Receiver

The original Model 1355 interrogator incorporated a wide-band intermediate-frequency amplifier For some applications, a wide-band amplifier would be desirable in order to preclude the necessity for continual retuning of the local-oscillator cavity However, in cases where the frequency of the ground transmitter is monitored, a narrow-band intermediate-frequency amplifier is required In order to be useful for both applications, two separate intermediate-frequency amplifiers were provided, one wide-band and one narrow-band These two amplifiers can be interchanged depending upon the application of the VPDI Figures 3 and 4 show the over-all receiver-response curves of the wide-band and the narrow-band intermediate-frequency amplifiers, respectively

Video

Inasmuch as there was no requirement for automatic indication of distance, all of the search and tracking circuits were removed from the VPDI Distance may be measured by the use of the external oscilloscope In addition, the coder and the decoder were modified to permit selection of (1) proper code and decode spacings, (2) proper code and decode spacings minus 1 25 microseconds, and (3) proper code and decode spacings plus 1 25 microseconds Selection of the spacings is accomplished with the mode-tolerance switch

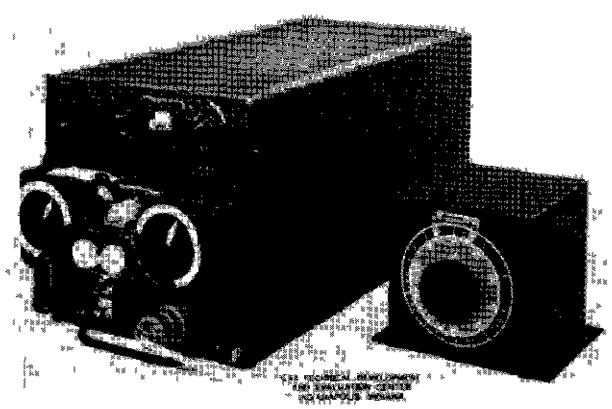


Fig 5 Photograph of VPDI

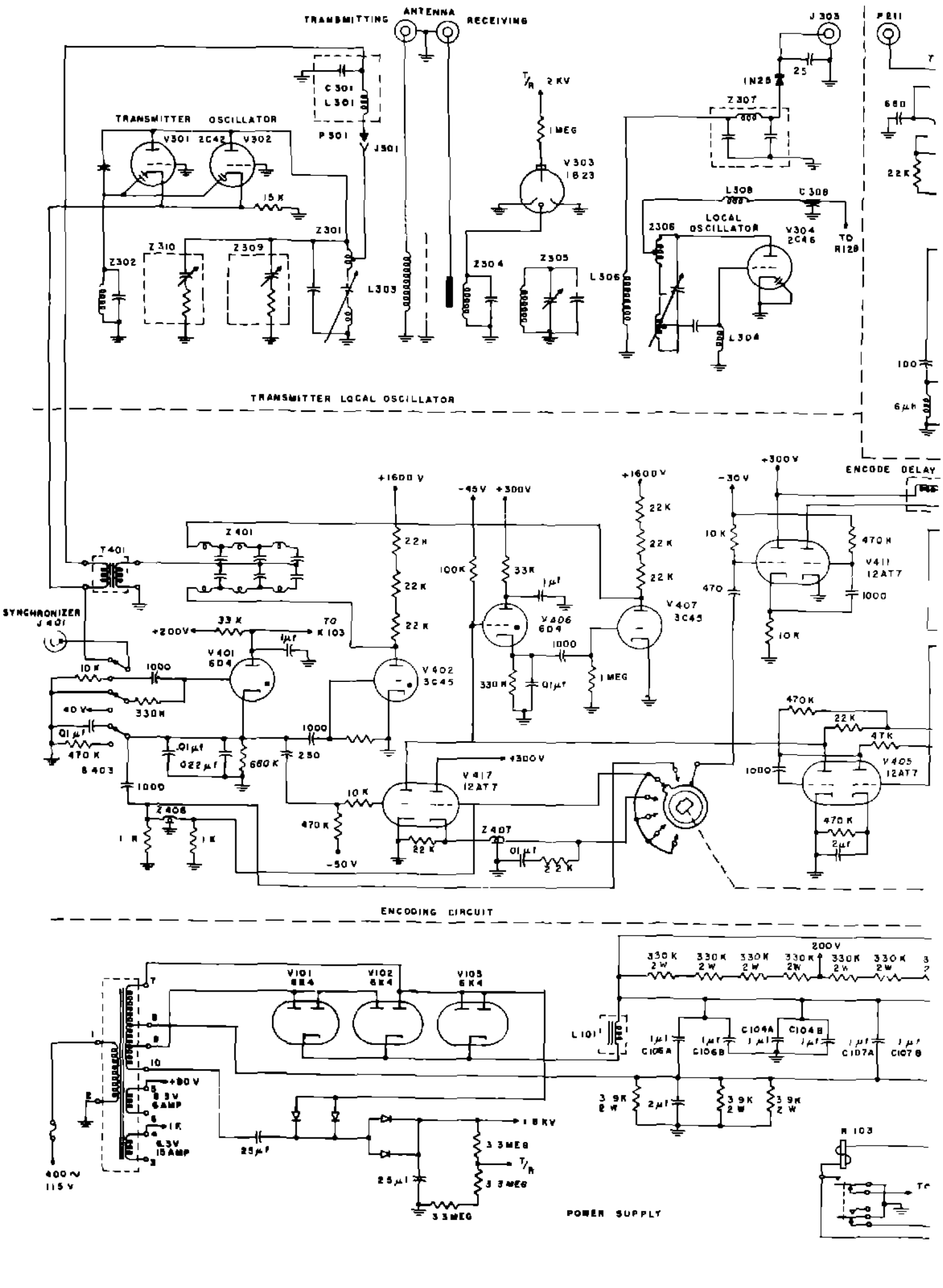
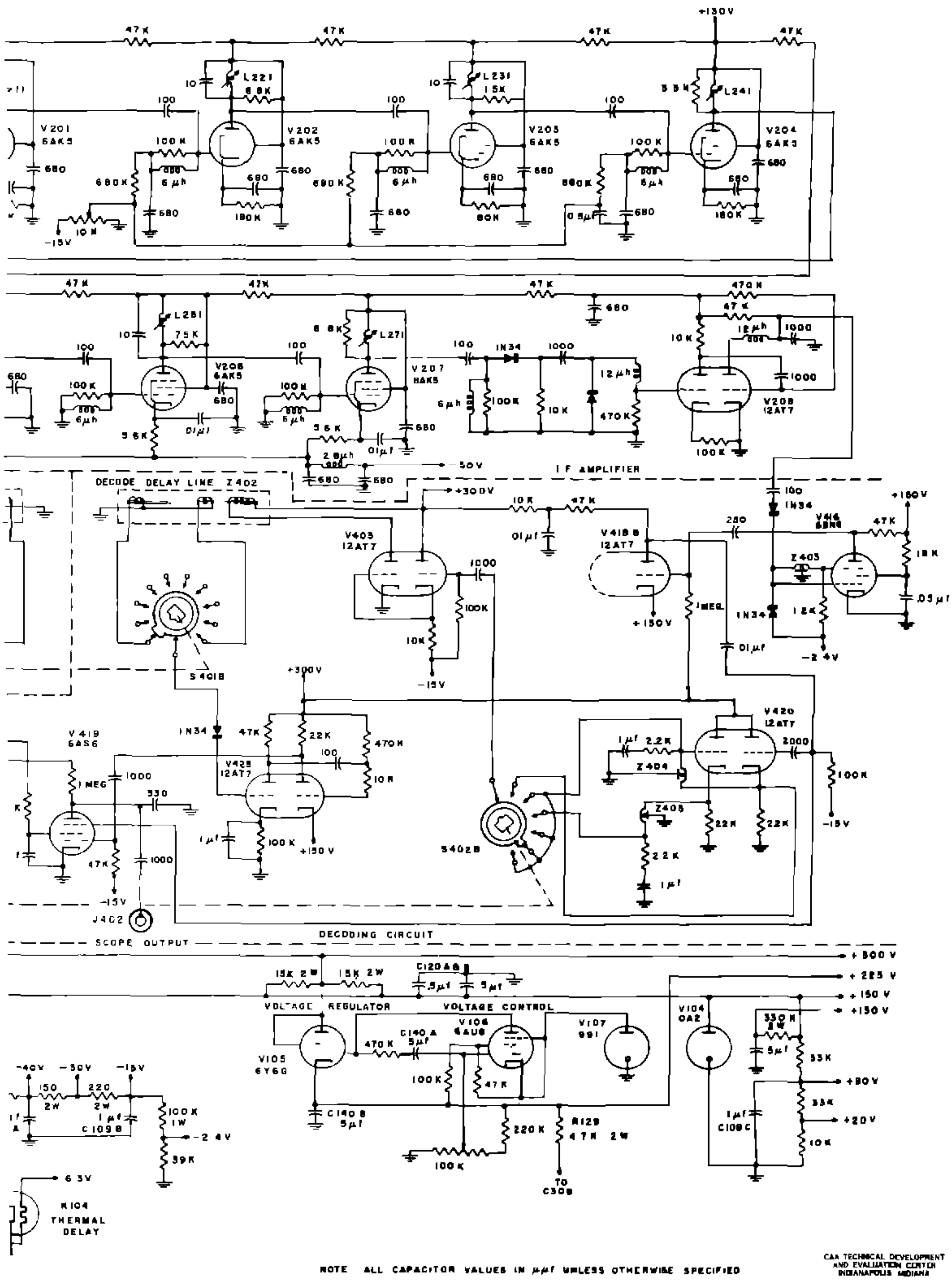

TRANSMITTING
ANTENNA
RECEIVING
TRANSMITTER OSCILLATOR
LOCAL OSCILLATOR
TRANSMITTER LOCAL OSCILLATOR
ENCODE DELAY
SYNCHRONIZER
ENCODING CIRCUIT
POWER SUPPLY

Fig. 6 Sch



+130V
L221
L231
L241
V201 6AK5
V202 6AK5
V203 6AK5
V204 6AK5
L251
L271
V206 6AK5
V207 6AK5
V208 12AT7
IN34
I F AMPLIFIER
DECODE DELAY LINE Z402
V403 12AT7
V418 B 12AT7
V416
Z403
S401B
+300V
V419 6AS6
V425 12AT7
V420 12AT7
Z404
Z405
S402B
J402
SCOPE OUTPUT
DECODING CIRCUIT
+300 V
+225 V
+150 V
+150 V
VOLTAGE REGULATOR
VOLTAGE CONTROL
C120 A&B
V105 6Y6G
V106 6AU6
C140 A
C140 B
V107 991
V104 OA2
R129 47K 2W
TO C308
+80 V
+20 V
C109 C
C109 B
-40V
-30V
-15V
-2.4V
6.3V
K104 THERMAL DELAY
NOTE ALL CAPACITOR VALUES IN μμf UNLESS OTHERWISE SPECIFIED
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am of VPDI

Magnetostrictive delay lines are employed to determine the basic code and decode spacings, and series-lumped constant lines are employed to provide the plus and minus variations It was necessary to replace the 30-microsecond magnetostrictive delay line with two longer lines to accommodate the longer code-and-decode spacings of the 100-channel system

Modulator

The original 1 5-microsecond pulse-forming lines in the modulator were replaced with 2 5-microsecond lines in order to meet the requirements of the 100-channel DME system

Power Supply

The power supply is identical to that of the older Model 1356 interrogator, except that the high-voltage supply is supplemented by two additional rectifiers to provide power for the wider modulator pulses generated by the longer pulse-forming lines

A photograph of the VPDI is shown in Fig 5 The characteristics are given in Table I

TABLE I

SUMMARY OF VPDI CHARACTERISTICS

Radio-frequency power out (peak)	4 0 kw
Transmitter-frequency range	945 - 1005 Mc
Receiver-frequency range	1168 - 1228 Mc
Receiver sensitivity (narrow i-f)	-85 dbm
Receiver sensitivity (wide i-f)	-82 dbm
Receiver, 3-db bandwidth (narrow i-f)	1 Mc
Receiver, 3-db bandwidth (wide i-f)	5 Mc
Local-oscillator settability	50 kc
Transmitter settability	50 kc
Power consumption	180 watts at 115 volts, 400 cps
Dimensions	Standard ATR base, 10 1/4 inches high
Weight	47 pounds

THEORY OF OPERATION

A wiring diagram of the VPDI is shown in Fig 6 Operation of the VPDI is controlled by the master oscillator V401 This oscillator generates an initiating pulse that ultimately results in two radio-frequency interrogation pulses being radiated from the transmitting antenna The master oscillator has two methods of operation controlled by the INT - EXT switch S403

When this switch is set to the INT position, the master oscillator is self-triggering and the pulse repetition rate (prf) is determined by the resistance and capacity in the cathode circuit of the thyratron relaxation oscillator The resistance-capacitance circuit is designed to produce 32 pulses per second

The other operating condition is selected by turning the INT-EXT switch, located on the front panel, to the EXT position. The master oscillator is no longer self-triggering, because a negative bias is applied to its grid. An external triggering pulse of positive polarity is applied to the grid via the external synchronization (sync) jack J401. The prf is determined by the external source of triggering pulses, since the oscillator will fire only once for each trigger input.

To avoid damaging the modulator tubes when the interrogator is initially turned on, the plate of the master oscillator is grounded by relay K103. After a fixed time which is determined by thermal time-delay relay K104 has elapsed, relay K103 is energized and is self-holding until the power is again removed.

The sharp positive rise in the potential of the master-oscillator cathode is used to trigger the first modulator tube V402. The gas-triode modulator tube rapidly discharges the charge stored in the pulse line Z401A. The discharge of the pulse-forming line through the primary winding of T401 causes a large, high-voltage, 2 1/2-microsecond pulse to be generated in the secondary winding of T401. This pulse is applied to the transmitter tubes V301 and V302 and causes them to oscillate at a frequency determined by the cavity dimensions which are varied by the external transmitter-frequency control. The transmitter oscillates and produces radio-frequency energy as long as the high-voltage pulse is applied.

In addition to firing the first modulator, the rise in potential of the master-oscillator cathode performs two other functions, one of which is to make the keyer tube V417A heavily conductive during the time of the first modulator pulse. Because of the low plate resistance of the conducting keyer tube, this effectively short-circuits the grid circuit of the second modulator trigger tube V406 which is prevented from firing because of stray pick-up from the first modulator.

The other function of the master oscillator is to drive the code-delay-line driver V411. Prior to being applied to the code-delay-line driver, the master-oscillator pulse passes through selector switch S402A. This selector switch has six positions. The first position transfers the pulse from the master oscillator to the code delay-line driver. The second position selects a pulse that has been delayed by Z406 for 1 1/4 microseconds after leaving the master oscillator. The third position selects a pulse that has passed through a total of 2 1/2 microseconds delay through Z406 plus Z407 and that is amplified by V417B to raise the level sufficiently to operate the code delay-line driver. Thus, no delay or a delay of either 1 1/4 or 2 1/2 microseconds can be added to the pulse derived from the master oscillator. The remaining three positions are used to determine decode spacing as explained later.

To supplement the variable delays available from the selector switch S402A, the magnetostrictive code-delay line Z401 is set so that each code coil is 1 1/4 microseconds short of the proper spacing. This allows the transmitter pulses to be set at the correct spacing or to be displaced ± 1 1/4 microseconds from normal, depending on the position of the selector switch S402A (mode tolerance control). The basic mode spacing is selected by S401A (mode control).

The output of the magnetostrictive code-delay line is quite low and is amplified by V405. The amplified pulse is applied to the grid of the second modulator trigger tube V406. The purpose of the trigger tube is to raise the power level of the pulse sufficiently to fire the second modulator V407. When the second modulator fires, it causes the transmitter tubes to produce a 2 1/2-microsecond burst of radio-frequency power in a manner similar to that of the first modulator tube. Control of the output radio-frequency power level may be accomplished in the transmission line through combinations of a directional coupler, a lossy line (attenuating cable), and a step attenuator.

Reply pulses from a transponder are received by a separate antenna and are injected into the preselector. The preselector consists of two tunable quarter-wavelength lines that allow the desired frequency to pass through to the crystal mixer CR301 but that attenuate signals which are removed from the desired frequency.

To produce an intermediate frequency of 59 Mc, a local oscillator operated 59 Mc above the received frequency is employed. The local oscillator is tuned externally by the local-oscillator tuning control in a manner similar to that used to tune the transmitter. Signals are fed into the crystal mixer after having passed through low-pass harmonic filter Z307. The harmonic filter by-passes to the ground undesired signals whose frequencies bear a harmonic relationship to the DME reply frequency.

From the crystal mixer, the energy is fed to the first stage of the intermediate-frequency amplifier. The original intermediate-frequency amplifier is stagger-tuned to produce a bandwidth of 5 Mc at 3 db down. A second, similar, intermediate-frequency amplifier was realigned to produce a bandwidth of 1 Mc at 3 db down.

In addition, a sensitivity control is provided by the use of a variable bias on the second, third, and fourth intermediate-frequency stages The two intermediate-frequency amplifiers are interchangeable

The output of the intermediate-frequency amplifier is passed to the spike suppressor V416, which prevents the interrogator from passing narrow spikes beyond this stage Spikes can result from noise, from electrical equipment, and from DME transponders operating on adjacent channels The spike suppressor is essentially a coincidence stage in which the video is applied undelayed to the control grid and is delayed 1 1/4 microseconds when applied to the suppressor grid As a result, if the video pulses are shorter than 1 1/4 microseconds, no coincidence results and there is no output from the coincidence tube, but if the pulses are longer than 1 1/4 microseconds, the coincidence tube produces an output pulse that continues through the receiver

The output of the spike suppressor is amplified by V418 and is applied to the grid suppressor of the final coincidence tube V419 In addition, the output from V418 is fed into a stage similar to that used in the transmitter section to provide a choice of no delay, 1 1/4-microsecond delay, or 2 1/2-microsecond delay The mode-tolerance control S402B selects the desired output to drive the decoding delay-line driver V403 By the adjustment of the decoding delay line Z402 so that each decode delay is 1 1/4 microseconds short of the proper delay, a choice of decoding spacings ± 1 1/4 microseconds is available on any mode The basic decode spacing is selected by mode control switch S401B

The output of the decoding delay line is amplified by V425 and is applied to the control grid of the final coincidence tube V419 If the reply signals from the ground transponder are of the proper spacing, coincidence will result when the mode-tolerance control switch S402B is set to normal, that is, a 1 1/4-microsecond delay is selected The coincidence output is brought to jack J402 for convenience in observing the operation of the final coincidence tube

FLIGHT TESTS

A preliminary flight test was conducted during which it was discovered that the receiver sensitivity was inadequate and that an externally controlled intermediate-frequency bias was desirable The purpose of this initial test was to determine the practicability of tuning and adjusting the VPDI to the desired transponder by the use of the oscilloscope as a tuning and peaking indicator. After the necessary additional modifications were made, the equipment was tested on a more extensive flight.

The technique employed in tuning to the transponder under test consisted of the following steps

1 Set the mode switch for the proper mode, using normal position
2 Set the receiver frequency by the calibrated dial
3 Set the transmitter frequency by the calibrated dial
4 Set the preselector dial using the calibration chart attached to the VPDI
5 Observe the oscilloscope connected to the receiver output of the VPDI
6 Vary the transmitter tuning clockwise and counterclockwise until the transponder fails to reply on each side Set the transmitter tuning to the center point, that is, at proper frequency This assumes a symmetrical bandpass in the ground receiver
7 By successive reduction of the receiver sensitivity and by peaking of the receiver-tuning control, ascertain that the receiver is set exactly to the frequency of the transponder transmitter
8 Observe the decoder output and operate the mode-tolerance switch to ascertain whether the code and decode spacings are proper

It was noted that this complete procedure could be executed in less than a minute, which is comparable to the search time of conventional interrogators From this point on, the operator's problem consisted only of checking the settings from time to time to correct any drifts The short-term stability (one to two hours) of all adjustments was excellent

A total of six ground transponders were located within operating range of this test flight, as listed in Table II It should be noted that this assortment of transponders represents half each of the reply and interrogation channels assigned to the DME service and six of the ten modes

Excellent coverage was obtained from all stations Typical ranges at which synchronized reply signals were observed are shown in Table III

TABLE II

TRANSPONDERS EMPLOYED IN VPDI FLIGHT TESTS

Station	Reply Frequency (Mc)	Interrogation Frequency (Mc)	Mode
Indianapolis Glide Slope	1191 0	986 0	C
Indianapolis VOR	1208 5	971 0	H
TDEC Experimental	1188 5	973 5	E
Toledo VOR	1201 0	986 0	G
Dayton VOR	1211 0	966	I
Goshen, Indiana, VOR	1208 5	978 5	A

TABLE III

TYPICAL RANGES OBTAINED WITH VPDI

Station	Range (statute miles)	Altitude Above Ground (feet)
*Indianapolis VOR	153	10,000
TDEC Experimental	144	10,000
*Toledo VOR	132	8,500
Indianapolis Glide Slope	129	10,000
*Goshen VOR	124	8,000
*Dayton VOR	78	2,500

*Maximum ranges obtainable at altitudes indicated

The asterisk represents maximum ranges obtainable at the altitudes indicated, the unmarked entries were simply random observations. All of the limit ranges are in excess of the theoretical maxima for line-of-sight radio propagation. Operation of conventional interrogators at the distances recorded is rare, a fact which indicates that code-spacing frequency incompatibilities between the interrogator and the transponder usually exist to a certain degree either singly or in combination or that either power or sensitivity is degraded

In January 1954, the VPDI was installed in a B-36 aircraft at Ellsworth Air Force Base, Rapid City, South Dakota, and during a subsequent 14-hour flight, round-trip distances up to 250 miles were obtained at 40,000 feet At 15,000 feet, round-trip distances in excess of 200 miles were obtained. At 40,000 feet, a one-way signal (ground-air) was obtained at 314 miles with good signal-noise ratio.

CONCLUSIONS

The VPDI is an extremely versatile instrument for investigating field-strength patterns and the effect of the system instabilities. The flexibility of the VPDI permits examination of a specific DME system variable while the remaining variables are maintained under close control Use of external test equipment will permit monitoring of ground-station operating characteristics The VPDI should also be a useful tool for examining multipath interference and for photographic recording.

ACKNOWLEDGEMENT

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