DEVELOPMENTS IN DME INTERROGATORS

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DEVELOPMENTS IN DME INTERROGATORS

SUMMARY

This report describes some of the improvements which have been made to airborne distance measuring equipment since delivery of the first 100-channel equipment Only the interrogator, which is the airborne part of the equipment, is discussed No attempt is made to describe general principles of distance measuring equipment, but rather a description of the more recent improvements in circuits and techniques is given

INTRODUCTION

The purpose of this report is to make available to potential manufacturers and users of distance measuring equipment (DME) the laboratory and flight experience gained with the more recent DME interrogators at the Technical Development and Evaluation Center of the Civil Aeronautics Administration The work herein described has been conducted under a program specifically designed to determine the combination of techniques and circuits most likely to provide a reliable DME interrogator which meets operational requirements In the process of this investigation, it has been necessary to modify the equipment in order to meet these operational needs and to provide the required reliability These modifications are described in detail In many cases, improvement was achieved through the substitution of improved components which have been developed since the equipment was originally designed In other cases, a re-examination of the requirements and the limitations of the DME system has necessitated modifications

In recognition of the rapid and recent progress made in the art of DME and in the fluctuating system requirements, the reader should not construe the contents of this report as reflecting criticism on the design of any of the equipment discussed Such is not the intention

This report discusses recent developments in DME interrogators by describing both the earlier experimental interrogator of the Hazeltine Electronics Corporation and the more recent FTL Model DIA production prototype interrogator of the Federal Telecommunication Laboratories, Inc It presents test data for both and also an explanation of the changes made to the FTL Model DIA at this Center A brief discussion of new test equipment and other related subjects is included

DESCRIPTION OF EQUIPMENT

Before discussing the differences between the types of equipment, it is well to note their similarities Some of the more salient features that are common to both are listed in Table I Both interrogators will operate with the Hazeltine Model DTB ground transponders, which are to be installed at very-high-frequency omnirange (VOR) and at instrument landing system (ILS) sites throughout the United States However, the Hazeltine interrogator is an early experimental model, whereas the FTL Model DIA equipment is a preproduction model Some of the major differences between the two types of equipment are shown in Table II

The apparent complexity and lack of automaticity of the Hazeltine unit is due to the fact that the particular model made available was a converted 50-channel interrogator In order to make a 100-channel one available at the earliest possible date and solely for purposes of system evaluation, the contractor was instructed to disregard automatic features, form factor, and packaging The Hazeltine and FTL interrogators are shown in Figs 1 and 2 Fig 2 shows one of the Model DIA subchassis removed from the main chassis

Operation

The FTL interrogator is designed for remote-channel selection Mode selection, preselector tuning, and limiting of the automatic frequency control (afc) are accomplished automatically when the transmitter and receiver frequencies are selected The Hazeltine interrogator requires that the transmitter frequency, receiver frequency, preselector, and mode be set independently For experimental purposes, the Hazeltine equipment has some advantages because of its greater flexibility For example, if the transponder at the ground station is not being triggered, the transmitter frequency of the interrogator can be placed independently on either of the adjacent channels, and, if the transponder responds, this fact is evidence of frequency difficulties either at the airborne transmitter or at the ground receiver Nevertheless, as DME is added to the airways, remote-channel selection is invaluable

TABLE I

COMMON FEATURES OF HAZELTINE AND FTL MODEL DIA INTERROGATORS

Feature	Description
Transmitter	afc, stability ±400 kc
Receivers	crystal-controlled superheterodyne
Receiver frequency	1188 5 to 1211 0 Mc
Transmitter frequency	963 5 to 986 0 Mc
r-f pulse width	2 5 microseconds
Channels	100
Distance	100 nautical miles
Tracking-pulse repetition frequency	30 pulse pairs per second
Antenna impedance	50 ohms
Indicator	clock type

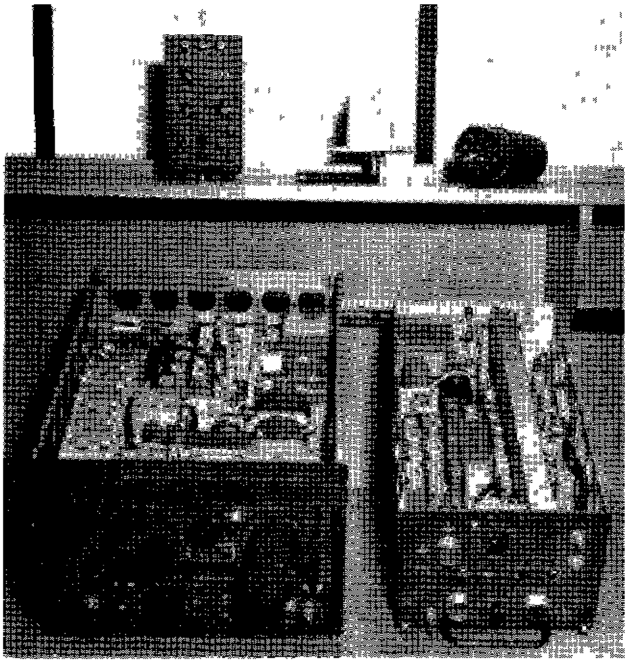

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Fig 1 Hazeltine 100-Channel Interrogator

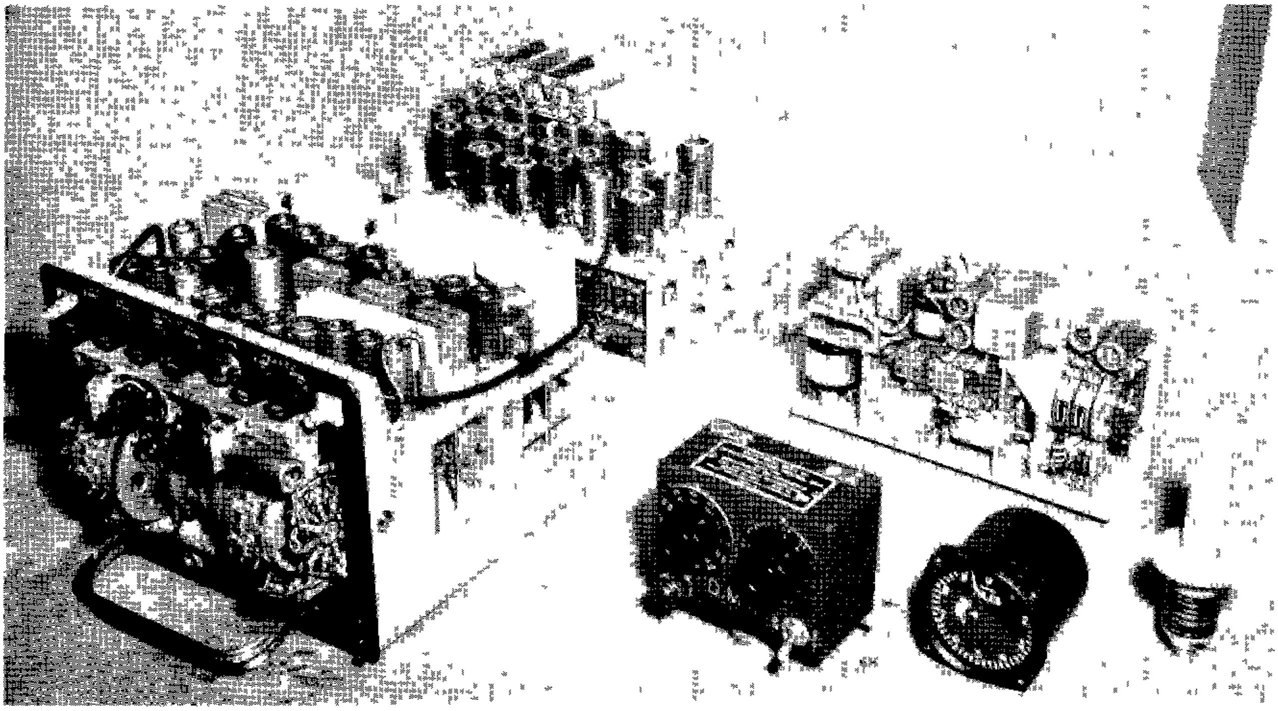

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Fig 2 FTL Model DIA 100-Channel Interrogator

TABLE II

COMPARISON OF HAZELTINE AND FTL MODEL DIA INTERROGATORS

Feature	Hazeltine	FTL Model DIA
Operation	Local and Manual	Remote and automatic
Channel selection	Manual	Motor-driven
Power consumption	350 watts, 400 cps 15 watts, 26 volts d-c	285 watts, 400 cps 11 watts, 26 volts d-c
Number of tubes	90	60
Receiver	One-crystal frequency	Multiple-crystal frequencies
Intermediate-frequency amplifier	Variable frequency	Fixed frequency
Transmitter afc	Multiple oscillators	Single oscillator
Ranging circuit	Linear saw-tooth	Incremental phase comparison
Memory circuit	Miller run-down circuit and position memory	Thermal relay and velocity memory
r-f power output	2 5-kilowatt peak	1-kilowatt peak
Weight	104 pounds	58 pounds
Size	Approximately 2 1/2 aircraft transportation racks (ATR)	Approximately 1 ATR

Remote-channel selection has been combined with the VOR omnirange control head so that selection of the desired VOR ground station automatically causes the interrogator to select the correct DME channel as set up in the DME and VOR pairing plan [1] Selection of a very-high-frequency (VHF) communication frequency above 117 9 megacycles (Mc) disables all power to the DME This system in conjunction with the Sperry rotatable panel pictorial computer is used in airplane N-181 at this Center The pilot's VOR receiver is paired with one interrogator and that of the co-pilot is paired with the other interrogator Thus, in the event that either of the VOR receivers or of the DME interrogators fail, the computer can be switched to the stand-by system

[1] "DME System Characteristics (Transition Period)," Radio Technical Commission for Aeronautics (RTCA) Paper 121-48/DO-24, Report of Special Committee 40, Dec 15, 1948

Channel Selection

Remote-channel selection in the FTL Model DIA interrogator is accomplished by a wafer-switch follow-up system When the drive motors of the drum are energized via relay, the drum and its follow-up wafer switch rotate until ground is found At this time the relay is energized and opens the drive-motor circuit The crystal drum has ten flat surfaces with intersections which actuate a microswitch in series with the follow-up wafer switch so that the turret will be stopped at exactly the right position for the crystal contacts Differentially geared to the crystal-turret shaft are two additional wafer switches which rotate at three times the speed of the receiver turret and synchronously with the transmitter turret These switches are wired to the encoding and decoding delay lines and thus automatically select the correct mode for the channel in use The crystal turrets also drive two cams and two lever systems whereby the preselector cavity is tuned and the afc limit switches of the transmitter are positioned

Number of Tubes

The FTL equipment has a total of 60 tubes, a saving of 30 tubes over the earlier Hazeltine equipment A circuit-by-circuit comparison would be meaningless because the two kinds of equipment are not comparable in such detail However, it can be said that large savings in tubes were effected in the tracking, afc, and indicator drive circuits

Receiver Tuning

The Hazeltine receiver uses a fixed-frequency crystal oscillator and multiplier chain to feed the mixer The intermediate frequency is different for each channel setting of the receiver, and the intermediate-frequency amplifier is step-tuned at each channel (frequencies 41 25 to 63 75 Mc) by a ten-position wafer switch for each stage As the channels are selected, the intermediate-frequency bias is changed and thus provides constant gain

The FTL Model DIA receiver contains one oscillator with the channel frequency determined by the crystal inserted by the crystal turret The mixer has a constant intermediate-frequency output at 30 Mc It is believed that the method used by the Federal Telecommunication Laboratories is the more desirable because it simplifies the intermediate-frequency tuning and lends itself readily to remote-channel selection

Adjacent-Channel Rejection

Radio-frequency (r-f) signals from transponders operating on a channel adjacent to the desired one (±2 5-Mc channel separation) have a tendency to develop signals on the desired channel In order to provide the attenuation required to prevent such pulses from reaching the tracking circuits, the Hazeltine interrogator employs a spike-suppressor circuit and a rather narrow intermediate-frequency bandwidth (approximately 1 3 Mc) Pulse signals of the adjacent channel appear on the selected channel as two spikes with a low plateau between them They are usually less than 1/2 microsecond in duration The entire video pulse, which is 2 5 microseconds long, is fed via a 1 1/4-microsecond delay line to the biased control grid of a coincidence tube and to the biased suppressor grid The resultant pulse output for wanted video pulses has a duration of about 1 1/4 microseconds, but the signal spikes of the adjacent channel are eliminated, since the pulse plateau between the spikes is of such low amplitude that it cannot cause conduction

The FTL interrogator employs a rather wide intermediate-frequency bandwidth of about 6 Mc and a Ferris discriminator to reject signals from adjacent channels The intermediate-frequency signal is applied to the discriminator, which is tuned so that it has a negative video output at the intermediate frequency of 30 Mc and a positive output at intermediate frequencies of 27 5 and 32.5 Mc The discriminator output is amplified by an amplifier that is sensitive to polarity This circuit provides a high degree of rejection, 70 decibels (db) to adjacent channels and somewhat less rejection to channels displaced more than 2 5 Mc

Both methods of adjacent-channel rejection are acceptable and have performed well during flight and bench tests The over-all effective bandwidth of each circuit is about 1 2 Mc The number of tubes required for adjacent-channel rejection is approximately the same either for spike suppression or for the Ferris discriminator

Transmitter

A Crystal Oscillator and Frequency Multiplier

The transmitter of the FTL interrogator has a single oscillator circuit and a crystal turret very similar to that used in the receiver This circuit utilizes one tripler and three doublers The Hazeltine circuit uses ten crystal oscillators and a doubler, the sixth harmonic beats with the transmitter output frequency The Model DIA circuit requires fewer tubes, and it switches crystals for channel changing The Hazeltine circuit connects B+ power to the desired channel oscillator Electronically, both circuits are of sound design

B Automatic Frequency Control

Both kinds of equipment employ intermediate-frequency amplifiers, a discriminator, and motor-drive circuits The circuits are similar except for the motor drive The Hazeltine circuit drives the afc motor in only one direction during frequency search, regardless of the channel and frequency selected The oscillator-cavity plunger is positioned by a cam which has a steep angle of climb for the retrace This method increases the time required to get on frequency and requires additional circuitry for blanking the frequency retrace in order to prevent the afc from tracking an image frequency during the retrace

The afc limit switch on the FTL Model DIA interrogator is positioned by the crystal-turret cam This limit switch has two contacts, and it brackets the afc cavity-plunger motor-drive gear by about ±1/8 inch When a channel is selected, the limit switch is repositioned and makes contact with the gear which is electrically ground This action causes the motor-drive tube to conduct in such a way that the motor drives the cavity plunger in the correct direction until the limit switch breaks contact with the gear and the discriminator regains control of the cavity-plunger drive motor This circuit reduces the frequency search time and the number of tubes required

C Modulator and Transmitter

The Hazeltine interrogator uses one 3C45 modulator tube for each pulse and two 2C42 transmitter tubes in parallel to provide a peak power output of 2 5 kilowatts (kw) The FTL interrogator uses one 3D21A modulator and one 2C39A oscillator to provide a peak power output of 1 kw Both power-output figures are approximate The desirability of the higher power output depends upon the relative strength of the air-to-ground and the ground-to-air paths With the increased receiver sensitivities now available in the Hazeltine DTB ground transponder, the r-f power of the FTL Model DIA is sufficient Both kinds of equipment will trigger the transponder at line-of-sight distances in excess of 100 miles

Ranging Circuits

The distance measuring circuits of the two makes of equipment differ greatly in the manner in which they measure the propagation time of the interrogation and reply signals In both, the effective time used to display distance is the time from the beginning of the second interrogation pulse to the beginning of the second reply pulse minus the 115-microsecond transponder delay The FTL interrogator ranging units involve both electronic and mechanical apparatus, whereas the Hazeltine circuits are entirely electronic The Hazeltine equipment measures time by the magnitude of a sweep voltage when the reply pulse appears on the sweep This method depends on the comparison of the sweep voltage with a calibrated range voltage generated by a cathode follower The sweep voltage has a time base approximately equal to the time required for a 100-mile distance, or 1,300 microseconds During search, the range voltage changes its amplitude over a period of about ten seconds, the search time The sweep voltage is applied to the plate of a diode, and the range voltage is fed to the cathode of the same tube The tracking gates are formed as the diode conducts This occurs when the sweep voltage equals or slightly exceeds the range voltage During search, the time interval between the start of the sweep voltage and the gate generation gradually increases as the range voltage increases, and this interval represents the position in time and distance of the tracking gates During track, the tracking gates control the range voltage and cause it to increase when the reply signal is in the wide gate (20 microseconds) and to decrease when it is in the narrow gate (10 microseconds) Tracking is accomplished at the center of the wide gate and at the trailing edge of the narrow gate The range voltage drives the distance indicator by means of a servo drive system It is evident that the range accuracy of this system depends upon the linearity of the sweep voltage and upon the calibration of the range voltage with the indicator A maximum error of approximately ± 2 miles and a zero distance error of ± 0 5 mile have been experienced with this equipment This method of distance measuring has been used extensively in surveillance and military-early-warning radars It is used for military fire-control radar only where the time length of the sweep voltage is very short, usually less than 150 microseconds This method is inherently less accurate than the phase-shifting method used in the FTL equipment Shaft rotation which is proportional to distance is available only by the use of a servosystem It is entirely electronic in nature and is quite adequate where extreme accuracy is not required and where a direct-current (d-c) instrument is used for distance indication This circuit also has instantaneous "jump-back" which does not require any mechanical motion Jump-back is defined as the initiation of search at less distance than the signal-loss distance

The FTL interrogator measures time by the sine-wave, phase-shift method The sine wave times the range circuits and the transmitter, and it delays the range-circuit action by a measured number of electrical degrees The phase-shifting goniometer is mechanically geared to the indicator servo-transmitters so that the indicator follows the angular position of the goniometer The goniometer can delay the range circuits by ten nautical miles, since the sine wave has a frequency of 8,088 cycles per second (cps) Additional delay for distances greater than ten miles is secured by the use of a phantastron with a maximum delay of about 1,300 microseconds, or 100 miles This additional delay is required only for the positioning of the tracking gates and has no effect upon the distance indicator The phantastron delay is controlled by a potentiometer which is also geared to the goniometer Thus, the error of the phantastron only needs to be less than ± 10 miles at any distance Early and late gates, each 10 microseconds wide, are used for tracking This is accomplished at the trailing edge of the early gate and at the leading edge of the late gate The over-all accuracy of this system is contingent upon the frequency accuracy of the master oscillator, the incremental delay of the goniometer, and the zero distance calibration This equipment is considerably more accurate than the Hazeltine system The distance error is so small that it is difficult to measure accurately with present test equipment The range unit of the FTL has shaft rotation available for computer input or indicator drive without the use of an additional servosystem This type of distance-measuring circuitry has been used extensively in military fire-control radar where a very high degree of accuracy is required

In the foregoing discussion the error introduced by the indicator proper has not been considered, since either equipment can drive several different types of indicators

Memory Circuit

Both systems use a memory circuit to prevent the ranging circuits from commencing search immediately upon loss of signal and to position the tracking gates advantageously upon receipt of the transponder signal

The Hazeltine interrogator employs a Miller run-down circuit to develop the actual memory time between 5 and 20 seconds In addition, a capacitor is charged during track, and at the completion of memory, this capacitor is connected to the circuit that generates the range voltage The capacitor voltage is of such polarity and amplitude that it causes the range voltage to decrease an amount equivalent to about ten miles This initiates search at a point less distant than the signal-loss point and obviates the necessity of a complete search in the event that the airplane is flying toward the transponder during memory The net effect of this circuit is to provide a position memory with jump-back The tracking gates are stationary during memory

The Model DIA circuit utilizes a thermal relay to provide the memory time A memory capacitor is also used in this circuit, but it is used during memory to cause the track motor to continue to track at approximately the same rate and direction as it did immediately preceding memory This action is referred to as velocity memory The jump-back feature is not used in this circuit The instant the replies fail and before the relays operate, another capacitor charge causes the velocity voltage to become more positive This increases the charge on the memory capacitor and has the effect of placing the signal point progressively more into the late gate during memory This action results in the further appearance of the returned signal in the late gate and prevents the circuits from going into search upon the return of the signal, as they would if the signal returned ahead of the early gate The change of velocity voltage may be seen in Figs 3, 4, or 5

Loss of the signal usually occurs when the airplane is in a turn or when the line of sight from the airplane to the transponder is broken by the curvature of the earth or by ground objects If the line of sight is broken by these obstructions, the pilot must select a different transponder or he must increase altitude Consequently, the memory circuit is most valuable during turns when the wing or some other aircraft structure interrupts the line of sight between the airborne antenna and the transponder antenna Either position or velocity memory is satisfactory During turns when a DC-3 aircraft with either top or bottom fuselage antennas is used, the loss of signal is usually of very short duration (less than 10 seconds for banked turns of 30°)

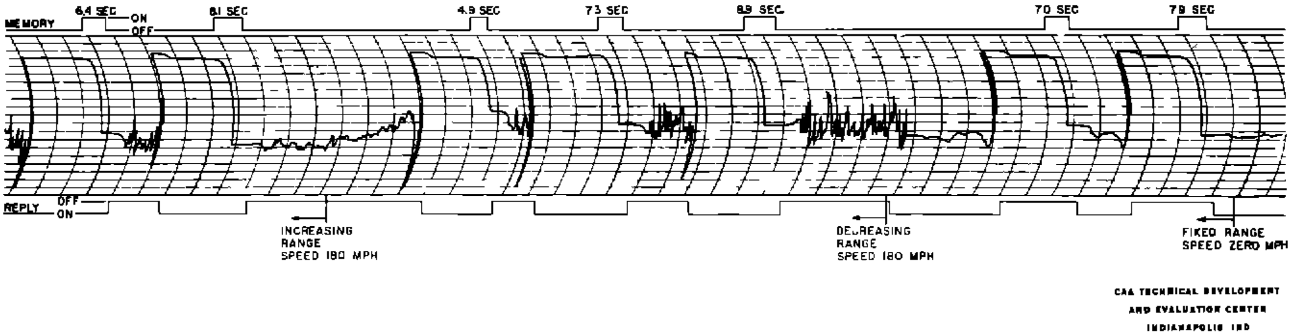

Fig 3 Velocity Voltage Using the Original Memory Circuit, Long Duration Reply Interruptions, Signal Generator, and Rate Simulator

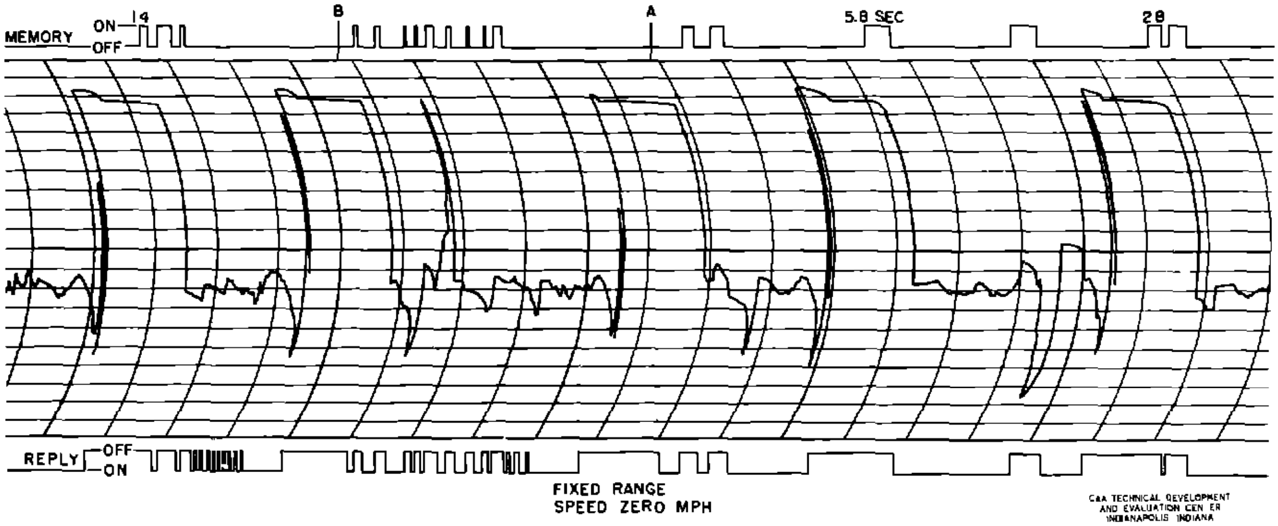

Fig 4 Velocity Voltage Using the Original Memory Circuit, Rapidly Fading Reply Signal, and Signal Generator

MODIFICATIONS OF THE FTL MODEL DIA INTERROGATOR

General

The purpose of most of the modifications described herein was to improve the reliability of the existing FTL Model DIA interrogators Some of the modifications were made to provide greater flexibility and standardization Modifications anticipated for the near future will be made with the same objectives in mind

The FTL Model DIA was designed to fulfill certain specifications Some of the modifications made to the equipment by this Center would not meet the same specifications Nevertheless, it is believed that in many instances it is desirable to sacrifice some performance for a gain in reliability

Memory Circuit

The memory circuit used in the equipment as it was received from the manufacturer cannot be relied upon to outlast a short signal fade, at times memory is entirely absent Because of the difficulties experienced at this Center with the original memory circuit, an investigation was initiated to determine the cause of this unreliability and if necessary to pursue the matter further and develop an improved circuit The memory circuit of the Model DIA is sound in principle, but the thermal relay destroys its effectiveness

Since the memory circuit had been giving erratic operation, it was decided to record the opening and closing interval of

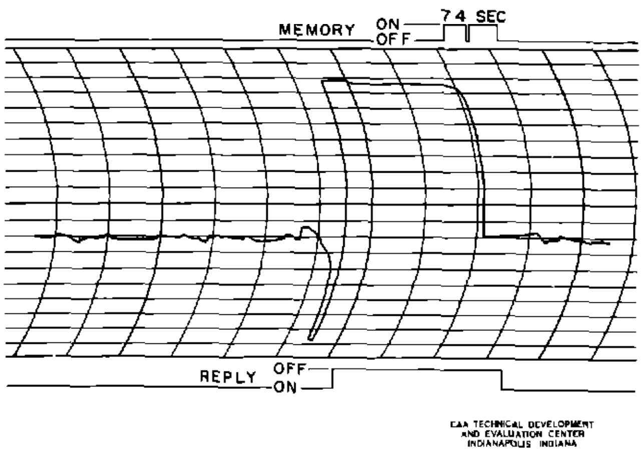

Fig 5 Velocity Voltage Using the Original Memory Circuit While the Transponder 83H is Being Tracked by the Interrogator Which is Stationary

the thermal relay at different ambient temperatures and after various periods of excitation and quiescence The relay was mounted on a breadboard in a controlled-temperature oven The operation of the relay may be divided into three separate phases

Phase I Voltage is applied to the thermal element of the relay, then heating occurs until the contacts open initially

Phase II Upon the opening of the contacts, voltage is removed from the thermal element of the relay, and cooling occurs until the contacts again close

TABLE III

THERMAL RELAY OPERATION

Oven Termperature (degrees C)	Relay No	Average Time Values of Multiple Trials Phase I Initial Memory (seconds)	Phase II Recovery (seconds)	Phase III Second Memory (seconds)
31	1	7 80	11 75	2 78
31	2	9 98	22 20	3 40
31	3	8 00	1 20	2 72
31	4	9 78	13 40	2 88
31	5	8 80	11 98	3 00
50	1	8 48	13 20	2 48
50	2	10 42	20 00	4 00
50	3	9 10	1 60	2 52

Phase III Voltage is immediately reapplied to the thermal element of the relay, and heating occurs until the contacts open a second time

Reference to Table III will readily disclose that

1 The oven temperature did not have a pronounced effect upon the operation of the relay within the temperature range used Temperatures within the interrogator average about 30° C above ambient

2 The initial memory time (Phase I) is not very consistent between relays

3 The closing time (Phase II) varies widely

4 The second memory time is much shorter than the initial one

Further study of the data presented in Table III reveals some of the inherent shortcomings of this relay which provides the memory in this type of circuit The extreme variation of operating time found in these thermal relays makes them noninterchangeable without prior testing of individual relays For example, when relay No 2 is used, the delay (Phase II) required for this relay to close after it had opened makes it possible for a condition to develop in which there would be no memory This can happen if the interrogator had previously lost the reply signal and had gone into full memory and search and had then locked on (found) the reply for only one or two seconds If the reply faded there would be no memory, since search has consumed 16 seconds, and it requires 22 2 seconds at room temperature and 20 0 seconds at operating temperature for this relay to close With the dust cover on, the operating temperature in the vicinity of the thermal relay stabilized at 54°C (30°C above room temperature) after three hours of continuous operation This leaves from 4 0 to 6 2 seconds during which there could be no memory Table III also reveals that memory would be decreased if the reply signal were lost shortly after tracking was resumed and after a previous loss of signal resulted in searching It will be shown later, by means of recordings obtained under operating conditions, that after one or more periods of signal fade a condition develops wherein there is greatly reduced memory Apparently, this is due to a rapid thermal build-up in the relay and a much slower dissipation of heat

While the DIA interrogators were being bench- and flight-tested, it was noted that there are instances when the interrogator immediately goes into search after the initial loss of the signal and without any memory whatsoever This is very undesirable, but it occurs infrequently While the exact cause is unknown, failure of the memory relay to close completely after a previous operation is believed to be responsible If the contacts were not completely closed, memory could not be started and the velocity voltage would

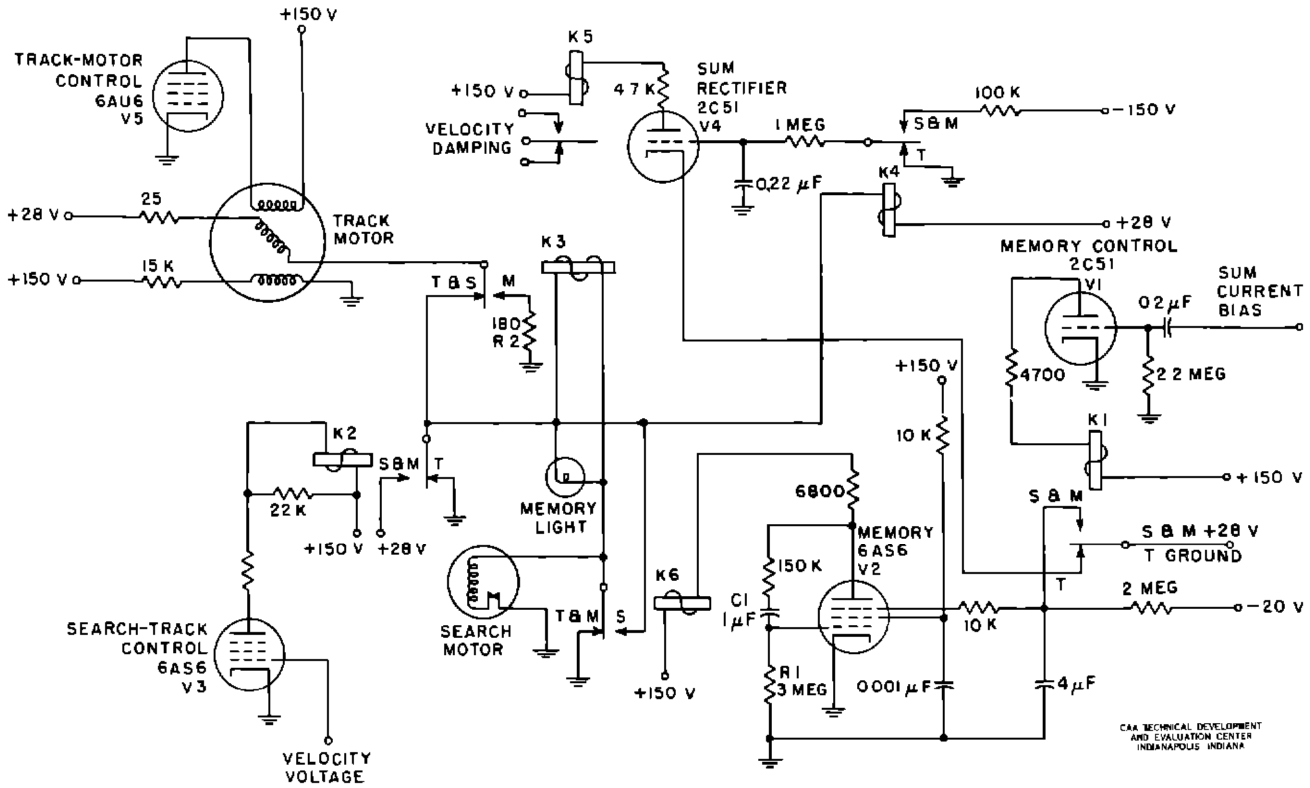

Fig 6 Modified Memory Circuit

rise rapidly This would cause the interrogators to go into search It is apparent that the characteristics of a thermal relay are not well-suited to the requirements of the memory circuit

The modifications made at this Center consisted of

1 Replacement of the thermal tube with a Miller run-down or discharge circuit
2 Removal of the velocity-memory feature
3 Addition of a run-back circuit which functions during memory

Fig 6 shows the circuit which was employed in place of the original circuit to provide memory In order to explain the operation of this circuit, let us assume that the interrogator is locked on a ground station and is tracking the replies normally A signal failure causes a loss of the coincidence pulse, and this results in a loss on tube V1 of the sum-current bias or the total of the positive and negative currents As V1 conducts, relay K1 is energized This relay applies 28 volts to grid No 3 of the memory tube V2 and thus removes the negative 20-volt bias that has held the tube cut off during tracking The tube then begins its discharge or run-down action which gives the circuit its popular name "run-down" The four-microfarad capacitor connected to grid No 3 of the memory tube 6AS6 prevents the circuit from entering the track mode until two or more coincidence pulses appear in the tracking gates These pulses consist of replies, noise, or fruit Fruit may be defined as interfering asynchronous pulse signals of random timing and amplitude Useless initiation of memory is thereby prevented

During track, condenser C1 has charged to the full plate voltage The instant grid No 3 loses its bias, the tube starts to conduct As soon as the tube begins conduction, the plate voltage drops and forces grid No 1 to become more negative through C1 Thus the conduction of the tube is opposed At the same time, C1 begins to discharge through the plate and grid circuits, and this discharge also causes the grid to become more negative This effect is cumulative and causes the plate current of the tube to rise at a very slow rate By varying resistor R1, a delay of approximately 4 to 20 seconds can be obtained The velocity voltage then rapidly rises to approximately 300 volts and causes tube V3 to become conductive Relay K2 energizes, and the following actions result

1 The memory light operates
2 Relay K3 energizes

3 Relay K4 is de-energized, and, after a short delay, K5 is de-energized

4 The armature circuit of the track motor is completed through resistor R2, which causes the track motor to run back in range at a rate set by the size of resistor R2

In this case, it runs back at approximately 250 nautical miles per hour At the conclusion of memory, tube V2 will conduct sufficiently to energize relay K6 This will cause:

1 The memory light to extinguish

2 Relay K3 to drop out or de-energize, thus stopping the track-motor run-back

3 Application of 28 volts to the search motor, which immediately operates

As soon as a reply is found, tube V1 will cut off and release relay K1 Thus, -20 volts is applied to grid No 3 of the memory tube V2, causing it to stop conduction Condenser C1 will charge to the plate-supply voltage in much less than a second and be ready to provide full memory again upon the loss of the reply pulses The reply pulses cause the velocity voltage to decrease and relay K2 to be de-energized This grounds the track-motor armature and allows the track motor to function The original condition of normal track is thereby established If at any time during memory the reply should return, tube V1 would stop conducting and relay K1 would be de-energized Thus -20 volts would be applied to the memory tube V2 and would cut off whatever slight current has built up The velocity voltage will also drop, causing tube V3 to release plate relay K2 This will

1 Extinguish the memory light

2 Release relay K3, thus stopping the run-back

3 Return a ground to the track motor, allowing it to track normally

There is a need for compensation because of the movement of the airplane during memory Velocity memory or run-back memory could be employed It was decided that run-back memory provided the most reliable all-round operation An analysis of the new memory circuit discloses that without the run-back feature the reply pulses will appear in the early gate if an airplane flies toward the ground transponder during memory and if the reply pulses return after a few seconds This analysis assumes that the reply pulses return before the airplane approaches so closely that the replies arrive prior to generation of the early gate The reply pulses which occur at the time of the early gate make the velocity voltage more positive As a result of the action of the track motor, the pulses can also initiate search before the late gate is intercepted To prevent the airplane from outdistancing the gates, run-back was included in the new circuit The speed of run-back can be adjusted to almost any value desired and only needs to be sufficient to equal the maximum ground speed that will be encountered by the airplane in which the interrogator is installed.

Graphic recordings were made of the operation of the thermal-relay memory circuit and of the Miller run-down memory circuit under similar conditions of operation These recordings are reproduced in Figs 3, 4, 5, 7, and 8 Figs 4 and 7 are especially significant since this type of fading is representative of that found during actual flight It is well known that at moderate and long ranges considerable fading is experienced when an airplane banks and turns in such a manner that it shields the airborne antenna from the ground transponder with part of its

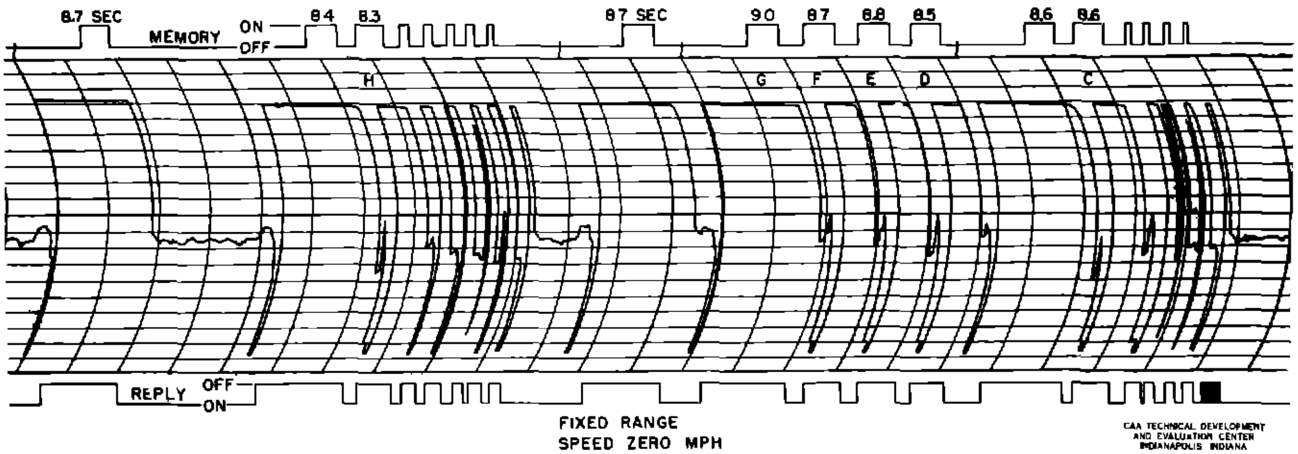

Fig 7 Velocity Voltage Using a Modified Memory Circuit, Rapidly Fading Reply Signal, and Signal Generator

structure Considerable fading is also encountered before the signal drops out near the maximum line-of-sight range

It will be noted from Fig 3 that the memory time produced by the thermal memory circuit varies considerably, from 4 9 to 8 9 seconds in this case The length of memory varies with the time that has elapsed since the last full memory expired In all cases recorded in Fig 3, this time exceeds 31 seconds It should also be noted that the longest memory occurred after the longest period of idleness These results were expected after the data on the thermal relay had been analyzed

Fig 8 reveals that the Miller discharge memory circuit is not affected by the period of idleness as the thermal-relay circuit is In fact, the period of longest memory, 10 0 seconds, occurred after one of the shorter periods of idleness, the shortest memory, 9 1 seconds, occurred after a relatively long period of rest Although this fact confirms much of the theory that has been presented, it does not reveal the major shortcoming of the thermal-relay memory circuit, which shortcoming is absence of memory Two instances are revealed in Fig 4 Points A and B indicate the position where memory should have been present but was not because the relay was at the threshold of opening or else was open because of the previous use of memory In the other instances where memory is present, the duration is notably short Fig 7 reveals that the discharge memory circuit retains its memory well and is always present, regardless of previous use or duration of memory Points C, D, E, F, and H are marked to indicate that memory almost ran out before the reply signal returned During this time the gates ran back at a speed of approximately 250 nautical miles per hour At this speed the gates will move inward 0 59 mile in 8 5 seconds, or the equivalent of 7 3 microseconds Since the gate is 10 microseconds wide, the signal will return within the late gate and the interrogator will lock on immediately It is interesting to note that even after the memory has almost expired (as at points D, E, and F), the full memory is consistently present if the signal fails (as at point G) Fig 5 was recorded to show the effects of the signal generator on the velocity-voltage jitter compared with that obtained when an actual ground reply is tracked at a fixed distance from the interrogator The results indicate that there is some additional jitter introduced but not an appreciable amount, and it should not affect the results of these tests In Figs 3 and 8, the track-simulator jitter is considerably greater than when the signal-generator set is used at a constant range, but this should not affect the results of these tests

Critical-Distance Coincidence

It has been observed that the FTL interrogator has a tendency to lock on the first reply pulse from a local ground transponder This ground transponder operates on Channel 19C at the Indianapolis ILS glide-path site The reply spacing for Mode C is 63 microseconds, therefore, the interrogator indicated 5 08 nautical miles too low or negative This particular ground transponder is located about +0 8 nautical mile from the interrogator antenna, therefore the interrogator indicates 4 28 nautical miles below zero, which is the result of -5 08 + 0 8 Actually, the needle which indicates the units pointed to 5 72 miles, and the needle which indicates the tens rested in the red sector of its dial

Further investigation revealed that at this unique range a double coincidence develops in the interrogator The additional pulses that must be present to produce this undesired coincidence appear to be caused by the mixture of a portion of the transmitted pulse with a continuous wave (cw) signal which is removed ± 30 Mc in frequency and which produces two pulses that pass into and through the intermediate-frequency stages of the interrogator These pulses appear in the video output of the receiver and are passed through the delay line In this case they are delayed 63 microseconds, the same as the

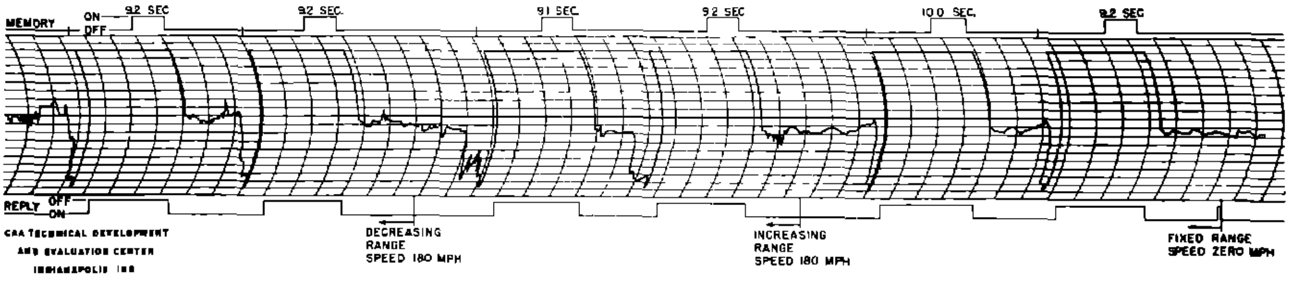

Fig 8 Velocity Voltage Using a Modified Memory Circuit, Long Duration Reply Interruptions, Signal Generator, and Rate Simulator

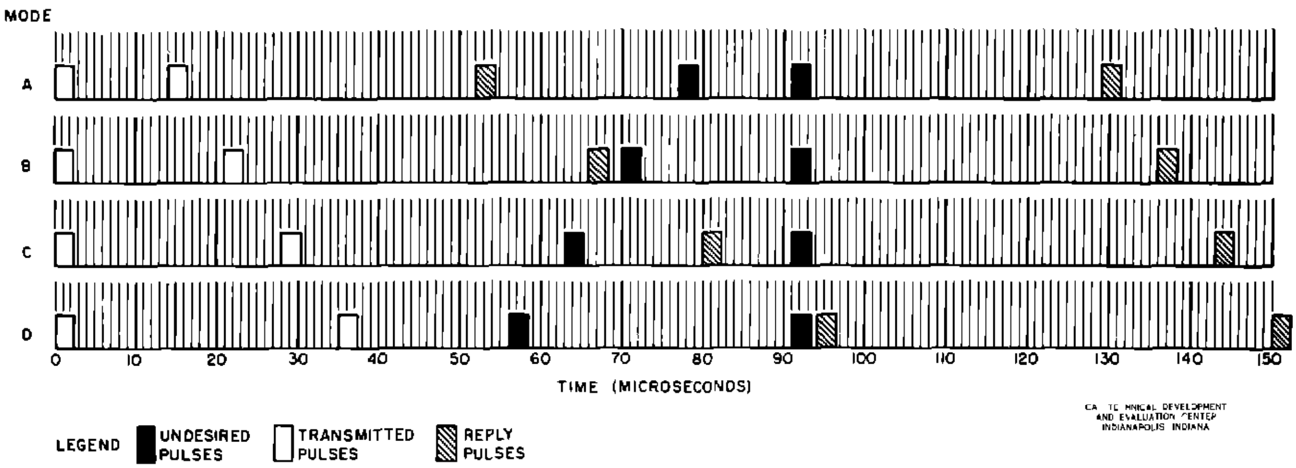

Fig 9 Critical Distance Coincidence

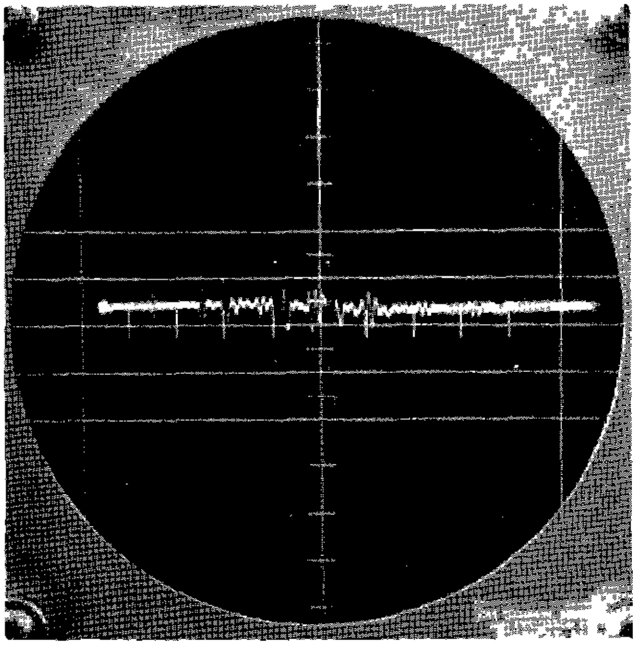

Fig 10 Critical Distance Delayed Video Using -3 Volts Bias

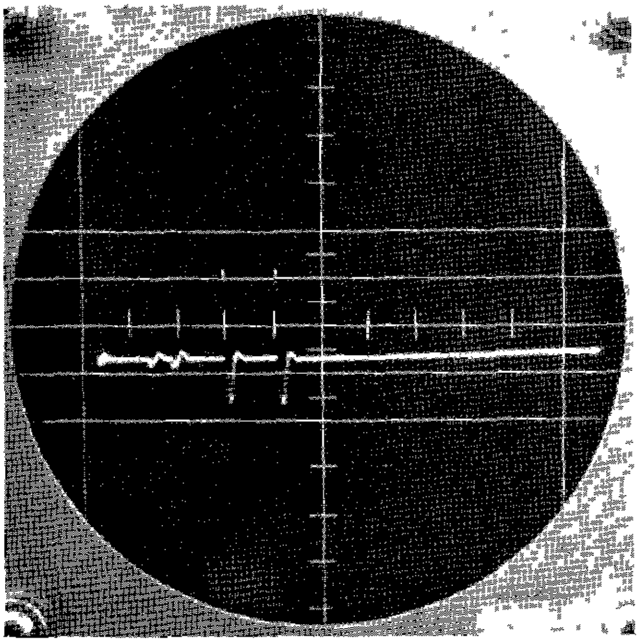

Fig 11 Critical Distance Undelayed Video Using -3 Volts Bias

reply pulses of the transponder These undesired pulses combine with the undelayed reply pulses of the transponder to form an additional coincidence The undesired pulses may be seen in Figs 10 and 11 The reply pulses return after a delay which is determined by the separation of the airborne and the ground equipment and by the fixed delay introduced by the ground equipment, but the position of the undesired pulses in the delayed video is determined by the decoder delay See Fig 9 Therefore, on each channel where these undesired pulses appear, multiple coincidence can occur at several separate and unique ranges provided that Mode A, B, or C is being used It can be seen from Fig 9 that, for all modes other than these three, this undesirable condition will not exist because both undelayed transponder reply pulses will not return until after the undesired pulses are produced On Modes A, B, and C, the undesired coincidences will occur at the ranges indicated in Table IV These coincidences will occur within a ±0 4 nautical mile tolerance because of the acceptance time of the decoder, but they should peak at

TABLE IV

CRITICAL DISTANCES

Mode	Range (nautical miles)
A	2 01 and 3 15
B	2 01 and 0 31
C	0 89

TABLE V

CRITICAL DISTANCE CHANNELS

Interrogator A	Interrogator B
05	05
08	08
13	13
19	19
24	31
31	46
59	64
70	70
80	80
91	

the ranges indicated If the 115-microsecond transponder delay is reduced, as it might be at some ILS installations, difficulty could occur on Mode D (for example, if the delay were reduced three microseconds or more)

Investigation into the sources of this phenomenon indicates that the heterodyning occurs in the mixer cavity of the receiver, the source of the cw signal is the multiplier chain of the receiver, and this cw signal heterodynes with the pulsed r-f of the transmitter These undesired pulses enter the intermediate-frequency stage in the first tube of the preintermediate-frequency amplifier together with the transponder reply pulses This phenomenon does not occur on all channels, and it can be predicted mathematically for some of the channels On others, its presence appears to be due to self-oscillations and complex mixing of the available harmonics

The undesired pulses which show up in the delayed-video circuitry have been consistently present on the channels shown in Table V Although this problem is by no means solved, considerable information about its causes and effects has been gathered Should it become a persistent source of difficulty in the future, it will be investigated further

First-Pulse Tracking

There is a tendency for all of the FTL Model DIA interrogators to lock on and track the first pulse of the transponder reply pair This malfunctioning occurs erratically and cannot be predicted or controlled consistently

A brief review of the coincidence-tube principle will establish the fact that coincidence will occur at every undelayed pulse applied to the tube if the undelayed pulses find their way to the delayed grid input When this multiple coincidence is present, the tracking circuits lock on and track the first coincidence pulse encountered, since the interrogator searches in the direction of increasing distance Because all circuits are calibrated to the second reply pulse for time measurement, the tracking of the first pulse creates a fixed error which is proportional to the reply-pulse spacing and which is always in the direction of reduced indicator reading This error varies with the mode from approximately one to six miles In the absence of this phenomenon, the only coincidence pulse present is the normal coincidence which is aligned in time with the undelayed second reply pulse The evidences of this trouble have been thoroughly investigated and assigned to (a) the presence of undelayed video reply pulses on the coincidence-tube delayed input, and (b) the presence in the video of noise which eventually finds its way, together with the undelayed and delayed video signals, to both coincidence grids

It is not known at present exactly how the undelayed pulses reach the delay-line output to the decoder and the delayed input to the grid of the coincidence tube It is believed that the causes are pickup within the delay line and the close proximity of delayed and undelayed circuitry Until the signal input is reduced below saturation, the desired delayed pulses at the control grid are approximately 9 volts When signal inputs greater than saturation were used, the undesired undelayed pulses varied in amplitude from approximately 1 5 to 5 1 volts About 4 volts at this grid will cause coincidence These voltages were measured with a Tektronix Type 511AD oscilloscope

This problem was taken under study by Federal Telecommunication Laboratories, and certain changes were made to one piece of equipment The modified equipment was returned to this Center, where extensive tests were performed in an effort to evaluate the effectiveness of the modifications made by the Federal Telecommunication Laboratories The results were not very consistent, but a multiplicity of measurements were made so that general trends could be observed The modifications which were made and an estimate of their effectiveness are listed in Table VI

Modification No 1 was the most effective change, but the reason for the improvement is not known Engineers of the Federal Laboratories advanced the thought that the coincidence-tube input is isolated from the delay line by the delay-line driver and that this isolation prevented delay-line ringing, or reflection, from reaching the coincidence tube However, it has not been possible to detect any delay-line ringing on the undelayed video During the implementation of the change, several leads were relocated This seemed to help, but previous replacement of some of the signal leads with grounded, shielded leads produced negative results This modification also increases the coincidence suppressor-grid bias, or undelayed-input bias from about -13 volts to about -30 volts The undelayed video which is fed to the coincidence tube is increased in amplitude from 35 volts to about 90 volts The increased amplitude of the undelayed pulses does not materially reduce the minimum delayed-pulse amplitude required for coincidence These voltages are outside of the characteristic curves of the 6AS6 coincidence tube for grid No 3, the suppressor However, various external and internal biases on both the delayed grid No 1 and the undelayed grid No 3 were tried without success prior to the modifications made by the Federal Telecommunication Laboratories After these modifications, the undesired pulses on the delayed grid varied from 1 5 to about 4 0 volts

Modification No 2 has a small effect upon the unwanted-pulse amplitude This change consisted of rerouting the delayed and undelayed pulse leads in the delay line so that the chassis acts as a shield over most of the length of the delay line This isolates the delayed and undelayed circuitry and thereby reduces crosstalk

Modifications Nos 3 and 4 would also tend to reduce pickup, but no measurable effect was produced

Modification No 5, similar to No 1, would block the delay-line ringing if it occurs

Modification No 6 was made to prevent mechanical damage and did not appreciably affect the test results

Modifications Nos 1, 2, 3, and 4 were installed in all FTL interrogators at this Center

As noted, the modifications decreased the probability that undesired pulses can become large enough to cause a first-pulse coincidence This fact has been substantiated by flight and bench testing Nevertheless, the unpredictable nature of this trouble prompts extreme caution when the probability of its future recurrence is contemplated If the undesired pulses are on the threshold of producing sufficient coincidence for lock-on and if noise coincidence is randomly present,

TABLE VI

FEDERAL TELECOMMUNICATION LABORATORIES MODIFICATIONS

No	Modification	Amplitude Reduction of Undesired Pulse
1	Connected undelayed coincidence input to decoder delay-line driver input	20 per cent
2	Rerouted delay line, shielded leads	5 per cent
3	Added delay-line transducer shields	Not measurable
4	Rearranged delay-line plug pins	Not measurable
5	Added rectifier crystals at decoder delay-line input	No effect
6	Increased spacing of mode-selection wafer switches	No measurable effect, but will reduce shorting due to mechanical shock

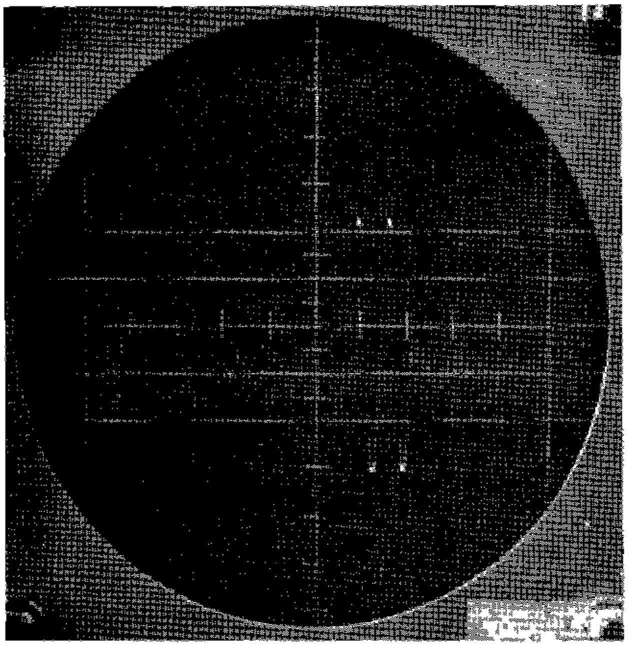

Fig 12 Undelayed Video Using Zero Bias

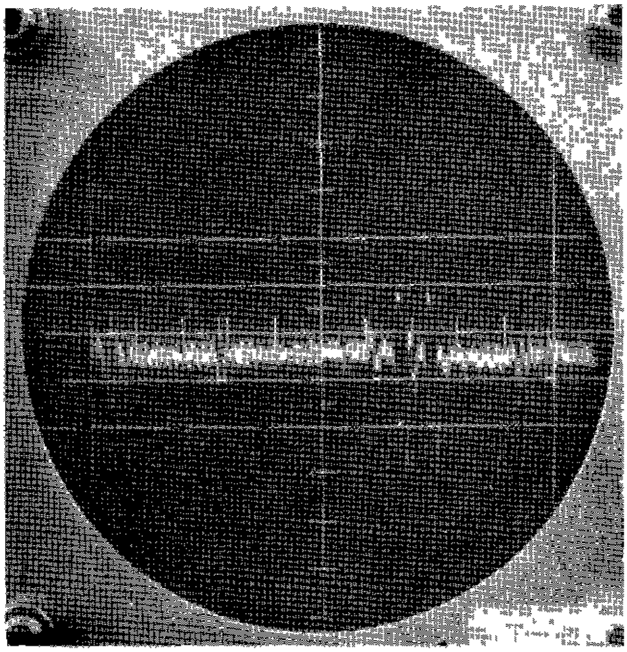

Fig 13 Delayed Video Using Zero Bias

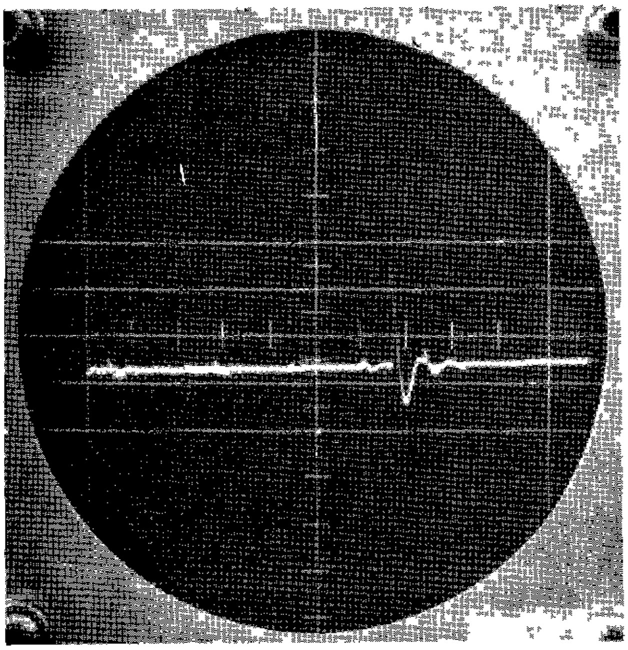

Fig 14 Coincidence Pulses Using Zero Bias

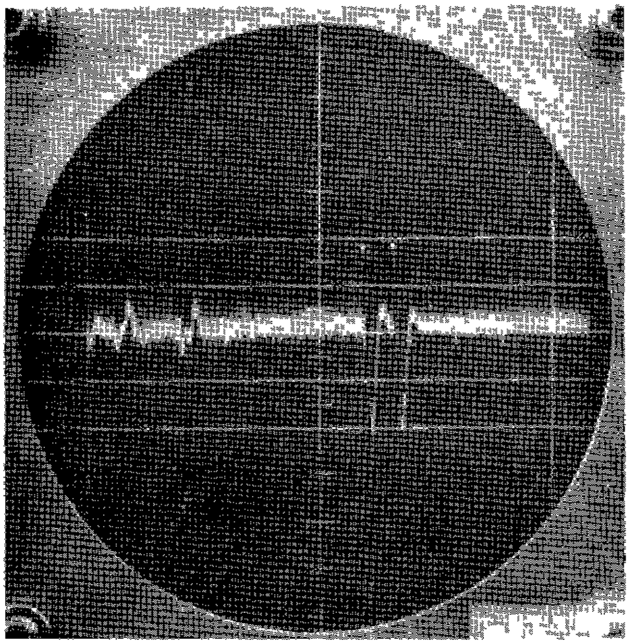

Fig 15 Undelayed Video Using -4 Volts Bias

the noise may cause first-pulse lock-on by effectively increasing the repetition rate of first-pulse coincidence This effect has been noticed on the bench and is the principal reason why it is necessary to set the intermediate-frequency gain at a fixed value The effect of gain on undelayed, delayed, and coincidence pulses of one piece of equipment is shown in Figs 12 through 17 Up to the present time, it has not been possible to establish a consistent relationship between the intermediate-frequency gain and the undesired, undelayed pulse size, however, the reduction of the noise coincidence also reduces the probability of placing three successive coincidence pulses in the late gate and thereby of initiating tracking of the first pulse Because of the large error introduced

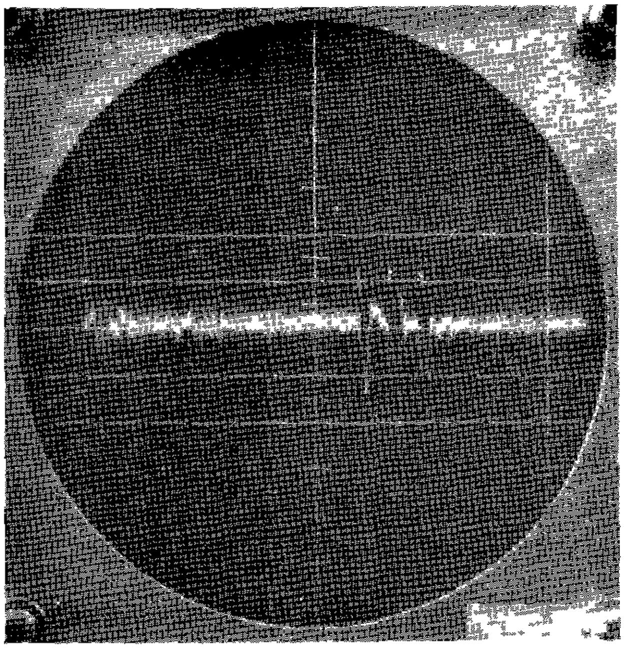

Fig 16 Delayed Video Using -4 Volts Bias

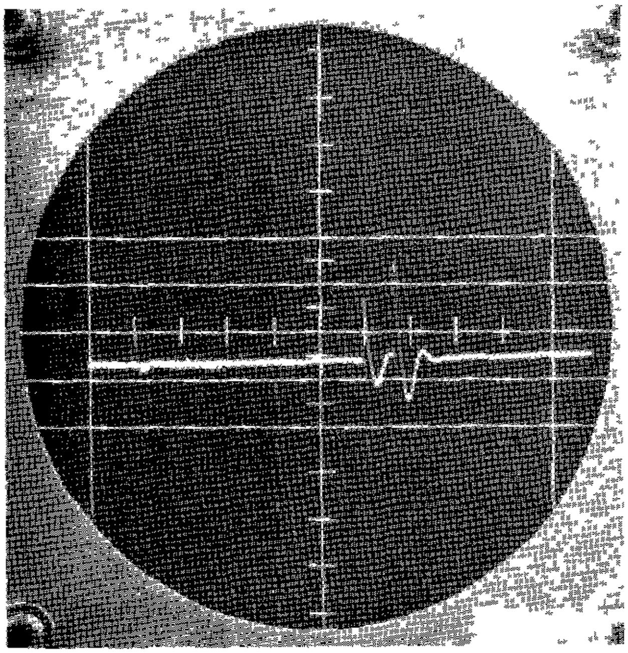

Fig 17 Coincidence Pulses Using -4 Volts Bias

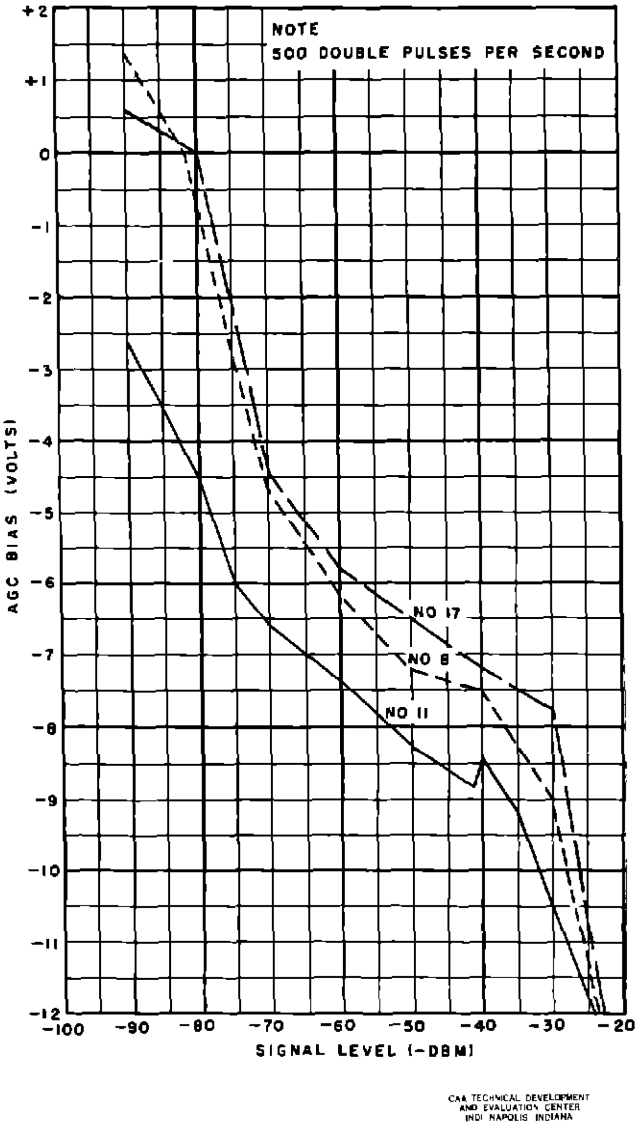

Fig 18 AGC Bias Versus Signal Level

by the tracking of the first pulse, this malfunctioning is considered quite harmful, and if it should recur, additional effort will be made to eliminate the cause of the trouble

Intermediate-Frequency Gain

The FTL interrogator automatic-gain-control (AGC) circuit has been analyzed, and considerable variation has been noted between units Fig 18 shows the variation in bias developed in three interrogators under identical conditions of operation With no signal input or maximum gain, the intermediate frequency has developed a bias of from +1 4 to -2 6 volts A similar variation existed at every input signal level

Fig 19 shows the variation of the intermediate-frequency bias voltage developed with varying input signal levels and different double-pulse squitter rates, or rates of triggering by noise It can be seen that the bias developed varies greatly with the double-pulse squitter rate At -20 db referred to one milliwatt (dbm), the change in bias from a no-fruit condition with a

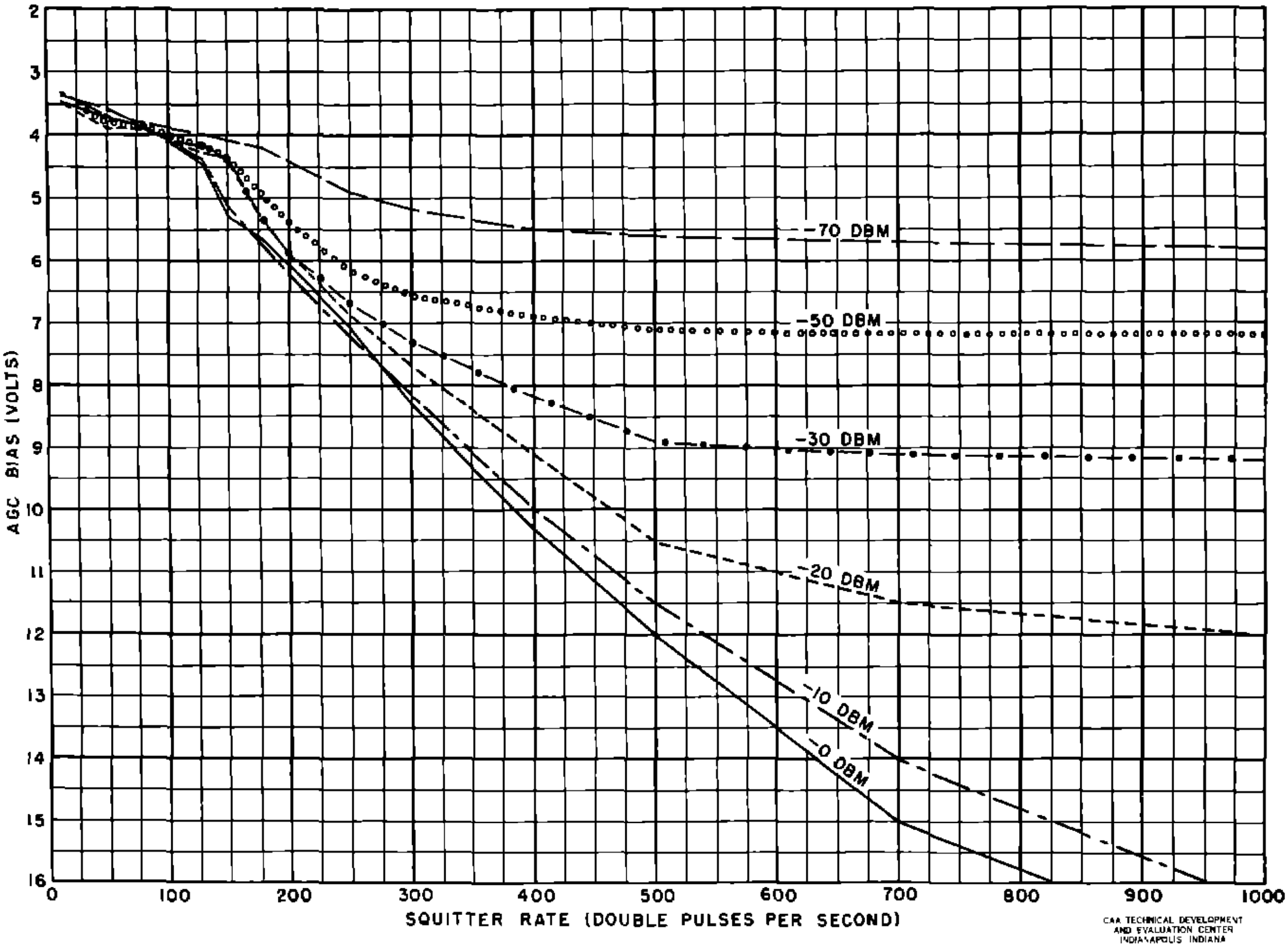

Fig 19 AGC Bias Versus Reply-Pulse Repetition Rate and Signal Level

pulse repetition frequency (prf) of 130 to a fruit condition of 800 pulse pairs with a prf of 930 is 7 6 volts This fact causes the noise in the coincidence circuits to be very hard to control and results in noise coincidence in the identity and tracking circuits If instead of using this interrogator another is chosen, the bias developed may be less, as indicated in Fig 18 The failings of this bias circuit are its response to fruit and its lack of consistency To overcome this excessive bias variation and to provide for more reliable operation, a fixed bias was installed This can be varied from 0 to -6 volts by means of a potentiometer Test flights have shown that the DIA interrogator will track out to the maximum range of 100 miles and will have a bias of -4 volts A 3- to 4-volt bias was required to provide a signal-to-noise ratio of 4 to 1 By improving this ratio, there is a reduction of the random coincidence which normally occurs when the gain is high and which at times causes the interrogator to lock on noise

There are also other problems that affect the final setting of the intermediate-frequency gain control The intermediate-frequency bias sometimes has a very pronounced effect on the severity of the undesired coincidence found at discrete ranges Figs 20 and 21 illustrate how the addition of -3 volts of bias accentuates this undesired condition As can be seen from Fig 22, a further increase in bias will improve the condition but the loss in sensitivity becomes objectionable

Another problem is the first-pulse coincidence found at all ranges Figs 12 through 17 illustrate this condition and reveal that it is sometimes accentuated by an increase in bias to about -4 volts A further increase in bias improves the condition, but again the loss in sensitivity becomes a limiting factor In some equipment, a bias of -3 volts will reduce the first-pulse coincidence

In flight testing, another problem has arisen which is dependent to some extent

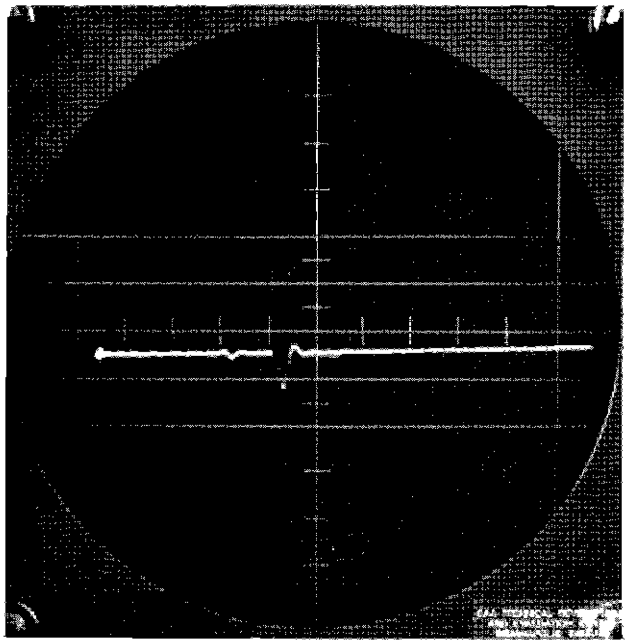

Fig 20 Critical Distance Coincidence Pulses Using Zero Bias

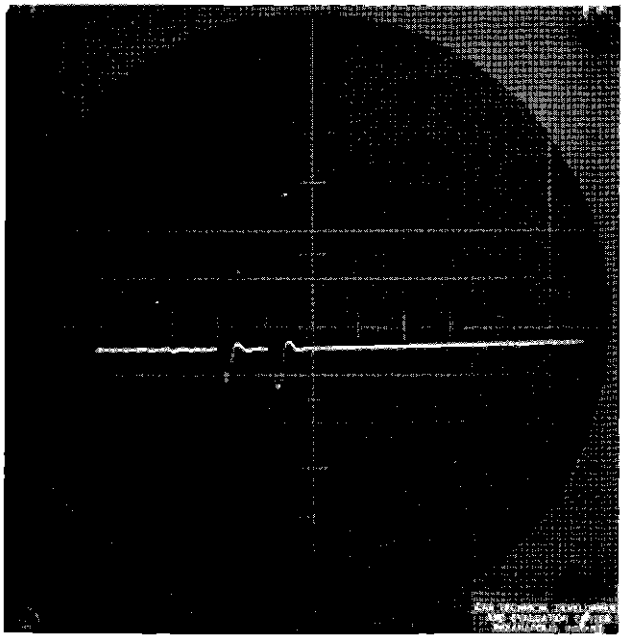

Fig 21 Critical Distance Coincidence Pulses Using -3 Volts Bias

upon intermediate-frequency bias During flight in close proximity to a transponder, it was found that there is a definite tendency for the second reply pulse to be de-energized This is especially severe if the reply spacing is small and if the airplane is almost directly over the transponder An increase in the

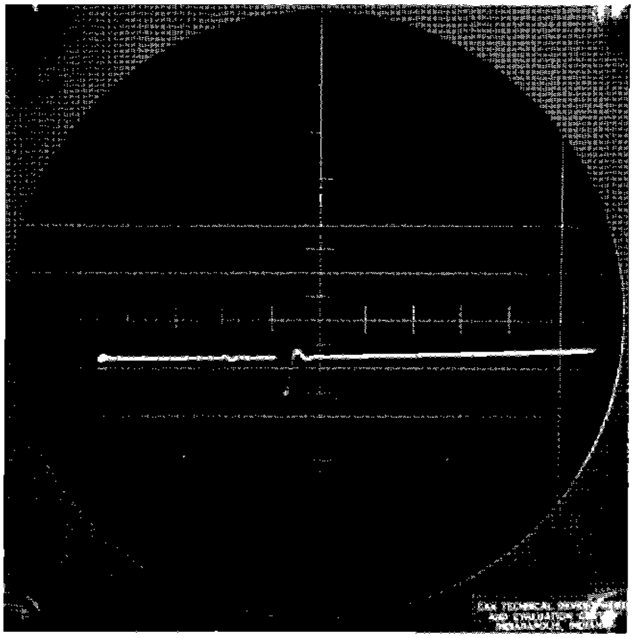

Fig 22 Critical Distance Coincidence Pulses Using -5 Volts Bias

intermediate-frequency bias consistently and considerably decreases this tendency, probably because the increased bias reduces the amplitude of first-pulse echoes which interfere with the reception of the second pulse

Although the three afore-mentioned difficulties are influenced by the bias used in the interrogator, they cannot be the determining factors in the choice of the bias value They are separate problems that need correction at their sources, rather than a compromise of the operation of other circuits to reduce their effect When the many factors involved are considered, it is believed that a bias of -3 to -4 volts is the best over-all compromise However, if other problems or conditions that necessitate a change in bias appear, it can be done quickly and reliably

Transmitter Frequency Shift

A General

It has been noted during the operation and flight testing of the FTL interrogators that a considerable shift in transmitter frequency occurs under conditions of track at 30 prf and search at 150 prf The cause of this frequency shift is not known There is also a smaller shift in frequency of approximately 250 kilocycles (kc) in most cases occurring between the first and the second transmitted pulses This shift in frequency is not serious, but the one between search and track is often of a much greater magnitude It has been known to exceed one Mc and often exceeds the allowable limits of ±400 kc To eliminate this shift, the four resistors in the prf-determining circuit were removed and a 680,000-ohm resistor was substituted to provide a constant prf of 55 Since there is no change in prf between track and search, there is no frequency shift, and this cause of unreliability has been temporarily eliminated The additional duty cycle imposed upon the transmitter tube will not shorten its life The plate dissipation at a prf of 55 is well within the allowable 100 watts

It is realized that this modification will substantially reduce the traffic-handling capacity of the system, as will be shown, but for the time being such modification provides a simple solution to a difficult problem It is not foreseen that the traffic density in the immediate future will be such that this modification will become a limiting factor By the time the traffic increases to a level where the full capacity of the system is needed, it is believed that new circuits and modifications will be available to make this change unnecessary A study is being made to determine whether the prf can be reduced to 30 for both search and track Either this reduction will be made, or the frequency-shift problem will be investigated more thoroughly

B Reduced Traffic-Handling Capacity at 55 prf

The International Civil Aviation Organization (ICAO) specifications for DME require that

> "The system shall be capable of including a transponder providing reliable service to at least fifty equipped aircraft in the presence of 1,950 other aircraft distributed over the remaining ninety-nine operating channels "
>
> "The interrogator shall be capable of successful search with transponder efficiencies as low as 67 per cent, and through random pulse levels up to 1,600 random pairs per second on each of the ten reply codes on the same reply frequency channel "[2]

To illustrate the effects of the increased tracking prf, the following computations which are based on the work of Hirsch[3] are included The symbols which are used in these computations are listed Those that are designated with a prime (′) refer to transponders which are interrogated by twenty aircraft

B	=	Transponder-reply efficiency
B''	=	Transponder-reply efficiency due to the maximum prf permitted by the designer
b	=	Number of replies
C	=	Number of transponders using the same receiver frequency
d	=	Duration of pulses (the effective duration is 1 5 microseconds)
ΔF	=	Average number of pulse pairs accepted by the decoder of aircraft A
F	=	Total number of replies by the transponders not directly interrogated by aircraft A
F_t	=	Total number of replies by all transponders
G	=	Duration of gate
g	=	Effective duration of gate
J	=	Total number of replies of acceptable spacing received if the desired transponder replies are blocked by the surface of the airplane
L	=	Length of search in microseconds
m	=	Number of challenges
N	=	Interrogations of inacceptable spacing from an average of 20 aircraft on each of the remaining nine channels having the same transponder receiver frequency
n	=	Interrogations intended for the transponder
N_E	=	Average number of false interrogations to be expected
N_F	=	Number of pulses passed by the gate
n_t	=	Effective number of interrogations

[2] Charles J Hirsch, "Traffic Handling Capacity of Paired-Pulse Coding for 100 Channel Distance Measuring Equipment (DME)," Proceedings of the National Electronics Conference, Vol V, 1949, p 372

[3] Ibid , pp 366 – 386

$P_m(b)$ = Probability of the gate catching exactly (b) replies in m challenges

p = Probability

pps = Pulses per second

prf = Pulse-repetition frequency

Q = Number of pps required to terminate search

R = Total number of replies having proper spacing

S = The number of replies necessary to terminate search in a given number of interrogations

S_F = Number of times search will terminate on fruit

T_r = Transponder dead time (136 microseconds)

T_s = Time required to search 100 miles

u = Number of pulses expected in gate because of fruit replies from transponders other than the one interrogator A is using

W = Number of pulses required in gate to terminate search

w = Number of pulses expected in gate because of fruit replies

Total Effective Interrogation Rates

I Fifty-Aircraft Transponder

$n = 50 \times prf = 50 \times 55 = 2750$ pps

$N = 20 \times prf \times (C-1) = 20 \times 55 \times 9 = 9900$ pps

$N_E = 8dN^2 = 8 \times 1\ 5 \times 10^{-6}(9900)^2 = 1176$ pps

$n_t = n + N_E = 2750 + 1176 = 3926$ pps

II Twenty-Aircraft Transponder

$n' = 20 \times prf = 20 \times 55 = 1100$ pps

$N' = 20 \times prf \times [(C-1) - 1] + 50 \times prf$
$= 20 \times 55 \times 8 + 50 \times 55 = 11{,}550$ pps

$N'_E = 8d(N')^2 = 8 \times 1\ 5 \times 10^{-6} \times (11{,}550)^2$
$= 1600$ pps

$N'_t = n' + N'_E = 1100 + 1600 = 2700$ pps

Number of Replies for Conditions A and B

I Fifty-Aircraft Transponder

$$B = \frac{1}{1 + n_t t_r} = \frac{1}{1 + 3926 \times 136 \times 10^{-6}} = 0\ 6519.$$

Total number of replies per transponder

$Bn_t = 0\ 6519 \times 3926 = 2559$

However, the transponder is limited to 2000 pps and therefore B'' is actually in this case

$$\frac{2000}{n_t} = \frac{2000}{3926} = 0\ 509$$

II Twenty-Aircraft Transponder

$$B' = \frac{1}{1 + n_t t_r} = \frac{1}{1 + 2700 \times 136 \times 10^{-6}} = 0\ 7314$$

Total number of replies per transponder

$B'n'_t = 0\ 7314 \times 2700 = 1974\ 78$

III Total Number of Replies on Common-Reply Frequency

$F = 9B'n'_t = 9 \times 1974\ 78 = 17{,}773$ per second

from nine 20-aircraft transponders

$F' = B''\ n_t = 2000$ per second from one

50-aircraft transponder

$F_t = F + F' = 17{,}773 + 2000 = 19{,}773$ per second from all ten transponders

Determination of the Number of Fruit Replies

Number of replies to interrogations of other aircraft using the same transponder as aircraft A

$B''n_t \approx 0\ 509 \times 3926 = 2000$ pps

$\Delta F = 18dF_tF$

$= 18 \times 1\ 5 \times 10^{-6} \times 19{,}773 \times 17{,}773$

$= 9488$ pps

$R = B''n_t + \Delta F = 2000 + 9488 = 11{,}488$ pps

$J = 18d(C-1)(C-2)(B'n'_t)^2$

$= 18 \times 1\ 5 \times 10^{-6} \times 9 \times 8 \times (1974\ 78)^2$

$= 7581$ pps

Determination of the Number of Fruit Replies Accepted by the Gate in One Second

$g = G + d = 20 + 1\ 5 = 21\ 5$ microseconds

I Interrogator Interrogating the Fifty-Aircraft Transponder

$N_F = gR = 21\ 5 \times 10^{-6} \times 11{,}488 = 0\ 24699$ pulses per interrogation

or

$N_F prf = 0\ 24699 \times 55 = 13\ 58$ pulses per second

II Interrogator Interrogating the Fifty-Aircraft Transponder But Not Receiving Replies

In this case the interrogator was not receiving replies because of the shielding of the antenna by a surface of the airplane

$N'_F = gJ = 21\ 5 \times 10^{-6} \times 7581$
$= 0\ 16299$ pulses per interrogation

or

$N'_F \times prf = 0\ 16299 \times 55 = 8\ 964$ pulses per second

Determination of the Number of Pulses Found in the Gates Under Various Conditions

I Minimum Number of Pulses Required in Gate to Terminate Search

Q = 21 pps, the number of pulses required to terminate search as measured at this Center

L = 12 38 x 100 = 1238 microseconds, length of search

T'_s = 16 seconds, time required to search 100 miles

$$W = \frac{T'_s gQ}{L} = \frac{16 \times 21\ 5 \times 10^{-6} \times 21}{1238 \times 10^{-6}} = 5\ 835$$

II Number of Pulses Due to Fruit Replies Expected in Gate

T_S = 20 seconds because of increased search time to be created in immediate future

$$w = \frac{T_s g N_F prf}{L} = \frac{20 \times 21\ 5 \times 10^{-6} \times 13\ 58}{1238 \times 10^{-6}}$$

$= 4\ 716$ pulses

III Number of Pulses Expected in Gate Because of the Fruit Replies From Transponders Other Than the One That Interrogator A Is Using

$$u = \frac{T'_s g N'_F prf}{L} = \frac{20 \times 21\ 5 \times 8\ 964}{1238 \times 10^{-6}}$$

$= 3\ 113$ pulses

Frequency With Which Search Will Be Interrupted by Fruit

The probability of catching S or more replies is

$$P_5(\geqq 2) = 1 - P_5(0) - P_5(1)$$

$$P_m(b) = \frac{m!}{b!(m-p)!} p^h (1-p)^{m-h}$$

$p = N_F = 0\ 247$

$m = 5$

To simplify the calculations, we have changed the ratio of required pulse pairs needed to terminate search from $\frac{21}{55}$ to $\frac{2}{5}$

$$P_5(\geq 2) = 1 - (1 - p)^5 - \frac{5 \times 4 \times 3 \times 2}{4 \times 3 \times 2} p(1-p)^4$$

$$= 1 - (1 - p)^5 - 5p(1 - p)^4$$

$$= 1 - 0\ 235 - 0\ 3864 = 0\ 3786$$

Search will terminate on fruit every

$$\frac{m}{P_m(\geq S)} = \frac{5}{0\ 3786} = 13\ 2 \text{ interrogations,}$$

or S_F times per complete search

$$S_F = \frac{LP_m(\geq S)}{g} = \frac{1238 \times 10^{-6} \times 0\ 3786}{21\ 5 \times 10^{-6}}$$

$$= 21\ 79 \text{ times per search}$$

S_F at 30 prf = 4 6 times per search

It can be seen that search can be completed under heavy traffic conditions only after a large loss of time because fruit was locked on Therefore, it is not practical to use this high a value of prf with the system fully loaded as specified by ICAO[5] This value of prf is a temporary solution only, and either it will be reduced to a lower value or the cause of the frequency shift will be eliminated

Computer Output Standardization

The 1000-ohm potentiometer, which provides distance information for computer operation, is not standardized in the various Model DIA interrogators As the equipment was received, the zero distance resistance varied from about 50 to 100 ohms The overall resistance varied from 945 to about 1060 ohms In order to interchange interrogators, it is necessary to employ standardized computer potentiometers All computer output potentiometers used at this Center have been standardized at 5 ohms for zero distance and at 945 ohms total resistance The zero setting was made by disassembling the potentiometer and setting the wipers at 5 ohms with the interrogator mechanical-range unit positioned at zero distance The total resistance was standardized by shunting the potentiometer with a fixed resistor of such a value that it makes the parallel combination 945 ohms These modifications permit complete flexibility and interchangeability of interrogators and mechanical-range units

Flag Alarm

As received, the FTL interrogators did not have a flag-alarm output, but an external relay, operated from the search-track relay, has been added for this purpose This external relay can provide either 28 volts d-c or ground for flag-alarm purposes, the choice depending upon the companion equipment being used with the interrogator

[5] Ibid

VOR and DME Control Head

The remote-channel-selection feature of the FTL equipment makes it possible to select automatically the associated DME channel whenever an omnirange channel is selected by the pilot This eliminates the necessity of multiple-control heads and simplifies cockpit procedure

The dual control is accomplished by connecting wafer switches in the omnirange control head and wiring them so that the associated channel is selected In the installation made at this Center, the control-head wafer switches provide ground for the interrogator-turret follow-up wafer switches A VOR and DME pairing plan must be consulted as a guide for the wiring of any particular installation The Collins control head used at this Center contains a 1-Mc DME wafer switch with a wide wiper and five contacts which make contact at two detent positions instead of one This necessitates the use of an additional multiwiper wafer switch which energizes and de-energizes a relay at alternate detent positions so that ground is provided via relay at only one of the two detent positions on the five-contact wafer switch This arrangement was used for the control of the reply frequencies The interrogation frequencies utilize a ten-contact, 1/10-Mc wafer switch A rectifier is energized at all control-head Mc-detent positions until 118 0 Mc or above is selected, at which time the rectifier is de-energized and the power relay supplying the interrogator drops out This action prevents DME operation when VHF communication is being used

Search Motor

Considerable difficulty was experienced because the search motor of the FTL Model DIA interrogator often failed to operate An investigation of the trouble revealed that the governor contacts failed to pass current and thus opened the rotor circuit of the motor Considerable arcing of the governor contacts occurred, and this probably is a contributing cause to the unreliability

It was decided to abandon the use of a governor Instead, a gear box with a greater gear-reduction ratio is used in conjunction with an external series resistor to decrease the motor speed The resistor will be chosen so that the starting torque of the motor will be more than sufficient to start the gear train. Tests were conducted on the present equipment. It was found that a resistor of sufficient value to reduce the motor speed to one-half maximum does not reduce the starting torque below the minimum value that is necessary.

It is realized that a variation in supply voltage would cause a much greater variation in motor revolutions per minute (rpm) than would have occurred had the governor been retained. This should cause no difficulty because a slightly greater delay in completing search would consume only a few additional seconds, which delay is negligible compared to the delay experienced when failure occurs. These changes will eliminate the difficulty experienced with the governor and will provide for more reliable operation.

Front-Panel Test Points

During bench and flight testing, there was recognized a need for readily accessible test points which could be used for oscilloscope trigger and for video output. As a consequence, two Type BNC receptacles were added to the front panel of all Model DIA interrogators. These receptacles are wired to test points. Shielded RB/58U coaxial cable was used for the connections inside the dust cover. A Type BNC plug and receptacle were used at the subchassis connection in order to facilitate removal of the subchassis. The front-panel receptacles may be seen in Fig. 2. The possibility of providing the same type of connections for viewing the coincidence pulse is also being studied.

OTHER PROPOSED MODIFICATIONS

General

The problems and modifications discussed herein are somewhat speculative and are presented for the purpose of providing an indication of the work which may be found necessary in order to further improve the reliability of the FTL interrogators.

First-Pulse Coincidence

In the event that further bench and flight testing reveal a tendency for the FTL interrogator to lock on and track the first pulse of a reply pair, it will be necessary to extend the work which has been completed on this problem. One possible solution, and the most desirable one, would be to continue to track down sources of the undelayed-delayed crosstalk and thereby eliminate the undelayed pulses in the delayed circuits. This solution is also the most difficult to accomplish, especially if the delay line proper proves to be the major source of the interaction. At present it is very difficult to determine whether the undesired pulses are present at the delay-line output, because the output is of such low level. If the delay line is not the major source of the undesired coupling, another solution may be to reduce the undelayed-pulse amplitude in the decoder chassis to a value sufficient for coincidence operation (25 to 35 volts) and to move the final video amplifier and delay-line driver to a position isolated from the decoder chassis. This position would probably be under the main chassis of the interrogator. Such a change would reduce the voltage level of the undelayed pulses in the interchassis wiring and in the decoder and should reduce the pickup in the delayed circuits.

Another solution may be to take advantage of the difference in amplitude between the desired delayed pulses (amplitude about 10 volts) and the undesired undelayed pulses (maximum amplitude of 4 volts) as they come out of the delayed-pulse amplifier. This could be done by adding another amplifier biased to about -5 volts. This method would be fairly easy to implement by using a triode-pentode miniature tube which would fit in one of the present nine-pin sockets of the decoder. Some sensitivity may be sacrificed with this approach. This solution would involve toleration of the undesired pulses but elimination of their effects. It also depends upon keeping the undesired pulses below some minimum value, because, if they exceeded cutoff by even a small voltage, the amplified output would cause coincidence. If this problem should recur, it is not known which of the afore-mentioned solutions might be attempted. It is probable that further bench work would be done in an effort to evaluate accurately the effectiveness and the ease of implementation.

Trigger Failure

The trigger pulse from the master oscillator has failed on various occasions and with different types of equipment. Failure of this pulse prevents the accomplishment of time measurements and of encoding, thereby making the equipment completely inoperative. The cause of this trigger failure is not known. It is not due to line-voltage variations. The master oscillator is usually operating satisfactorily during the failure. It does appear to be related to the warmup and is more liable to occur when the equipment is cold. All waveforms associated with the trigger have been studied and seem to be adequate. The subchassis plugs do not appear to be causing this trouble. Because of the intermittent nature of this defect, it has proved quite difficult to isolate. Further work on this problem will be done when some of the more urgent problems have been solved

Subchassis Plugs

Some of the pin type of plugs which connect the subchassis with the main chassis have developed poor connections This defect can easily be detected by simply loosening the subchassis-retainer cap screws and moving the subchassis by hand In the more serious cases, the contact is open even after the cap screws are tightened In other words, the contact is poorest when the pins are properly aligned

Up to the present time, the plugs have simply been replaced with new ones However, a change from the pin type to the ribbon type of connector is being considered, and samples of the ribbon type of plugs have been secured Additional contacts are also needed on some subchassis in order to accommodate changes made at this Center It is anticipated that all interrogators at TDEC will be modified to utilize the improved type of plug

System-Standardization Measurements

The measurements referred to involve both the airborne interrogators and the ground transponders, but only the interrogator parameters will be discussed here When several transponders are utilized during a flight, it is of prime importance that all spacings and frequencies are standardized to such a degree that the pilot can be certain that the interrogator will track the transponder on the channel selected and only that transponder This necessitates having all the ground frequencies, air frequencies, and spacings within the tolerances of the system.

A method of measuring the decoder spacings of the interrogator within ± 0 3 microsecond and the transmitted-pulse spacings of the interrogator within ± 0 2 microsecond has been devised It is believed that this accuracy will be sufficient to insure reliable operation on airway flights The method used at this Center is more fully explained under the section of this report entitled "DME Test Equipment "

Transmitter and receiver frequencies of the interrogator need to be investigated quite thoroughly, and it is planned to conduct several flight tests in an effort to reveal any deficiencies This testing will be followed, if necessary, by laboratory investigations in order to discover the causes and possibly to correct any deficiencies which exist

Identity Operation

The operation of the identity circuits in the FTL interrogator has been checked in the laboratory and appears to be marginal The capacitors in the lumped-constant delay line of the identity circuit broke down, new type capacitors were then supplied by the Federal Telecommunication Laboratories for replacement of the defective ones It is believed that the identity circuits will require modification, but since they have had so little flight testing to the present time, reservation in judgment concerning them is in order

Crystal-Turret Position and Wafer Switches

It has been noticed that the crystal-turret wafer switches do not hold up well mechanically and that they are not properly aligned in all equipment The wiper, which is in series with the position microswitch, is not well-centered in its contacts when the turret comes to rest It is planned to attempt to correct these conditions On several occasions, these defects prevented the turret from coming to rest on the selected channel

Federal Telecommunication Laboratories replaced the original contacts, which made electrical contact with the turret drum, with microswitches This change was necessary because the original contacts became oxidized and failed to stop the turret It is believed that the actuating mechanism of the present microswitch can be improved by the replacement of the sliding actuator with a roller type of actuator These changes, combined with the changes explained under the heading "Channel-Changing Motor," should provide a very reliable channel-changing operation

Channel-Changing Motor

In several instances, the channel-selection drive motors failed to complete the channel-selection sequence because of insufficient torque While this mechanism does not stall very often, the crystal drum frequently falters and slows To overcome this, it was decided to increase the gear-box reduction ratio in order to increase the torque output and also to slow the channel-changing speed With the present speed of rotation, the crystal-turret drums often coast too far, and a slight jarring of the unit causes the channel-changing mechanism to cycle

A recent modification made at the Federal Telecommunication Laboratories consisted of removing resistor R103 from the channel-selection circuit and replacing it with two resistors, each of the same wattage but approximately one-half of the original resistance value The purpose of this modification was to prevent R103 from burning out during continuous channel operation These resistors, R103 and R104, are connected ahead of relay K101 so that they are not in series with the motor during braking

The original channel-changing mechanism completed one cycle in four to five seconds, but there is no necessity for such speed and a period of ten seconds would not be unreasonable It is planned to increase the torque and to slow down the channel-changing speed to approximately six or seven seconds for one complete revolution This should provide plenty of torque and should lessen the possibility of coasting by the selected channel

Computer Output

When the FTL interrogator is used with the Sperry rotatable-panel pictorial computer, the shaft rotation in the interrogator is changed to a voltage, and this is converted back to shaft rotation by a servosystem in the computer

It appears that the mechanical ranging unit of the interrogator could be placed in the computer, in which case the ranging unit would drive two potentiometers in the course-line computer instead of the present single potentiometer in the interrogator and would also provide direct mechanical shaft rotation for the positioning of the pictorial computer This arrangement would eliminate the computer servoamplifier and the course-line drive motor The accuracy of the computer would be increased by the elimination of this circuitry

Another possible arrangement might be to place only the goniometer and the pulse-selector potentiometer of the interrogator in the pictorial computer and to drive them by means of the computer-positioning drive motor In this case the pictorial-computer drive motor would position the two potentiometers of the course-line computer, the goniometer of the interrogator, and the pulse-selector potentiometer A means for providing retrace search would have to be added These plans have not been worked out in detail, but it is anticipated that a modification of this nature will be investigated and implemented if it is found advantageous

Dual-Antenna Operation

As the DME is added to the airways, it may develop that the present memory circuits are insufficient under all conditions of operation In the event that aircraft structures interrupt the line-of-sight path of the radio to the extent that the memory is exceeded or the loss of accurate continuous indication cannot be tolerated, a system for automatically switching to a second antenna may be desirable A circuit which accomplishes this operation has been devised and flight-tested See Fig 23

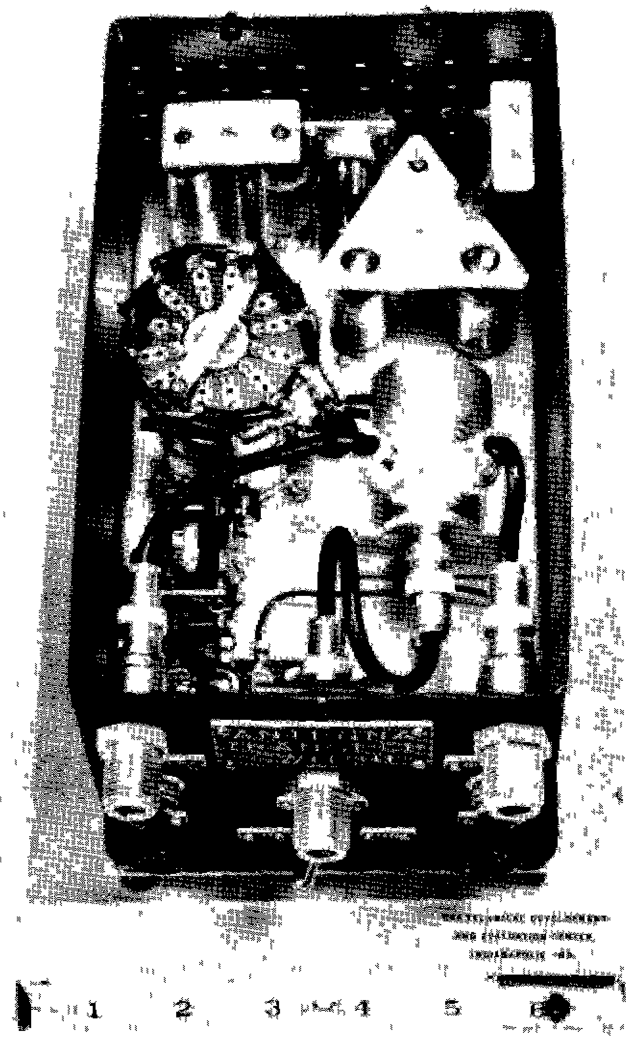

Fig 23 Antenna Transfer Switcn

Flag Alarm

A flag-alarm circuit is used to warn the pilot or to actuate the computer when the DME indicator reading is in error and should be disregarded An indicator flag-alarm circuit was added to the FTL interrogator at this Center The present circuit, with the new memory circuit added, provides a flag alarm during search and memory Since the equipment is inoperative during the 90-second warmup, it is planned to provide a flag alarm during warmup and search and to remove the alarm during memory Distance information during memory is useful information and will be displayed

Receiver Crystals

Four receiver crystals have become inoperative during bench- and flight-testing operations Some of the crystals have failed to produce oscillation, and some oscillate at an incorrect frequency The cause of this defect is not known Engineers at the Federal Telecommunication Laboratories are currently investigating the trouble It is not believed to be in the oscillator circuit, because the transmitter uses a similar oscillator circuit and its crystals have not given any difficulty to the present time Replacement of the crystal corrects the trouble Any necessary modifications to amend this malfunctioning will be made at this Center

Some difficulty has been experienced with the crystal-contact clips, they sometimes become deformed and fail to make contact with the crystal terminals If this trouble recurs, new clips will be designed and installed

Tachometer

The mechanical ranging unit uses a d-c motor as a generator for the remote-rate information This motor also provides a voltage which is compared with that of the velocity in order to produce an error-velocity voltage which controls the speed of the track motor This component is called a tachometer Several have developed open windings The cause of this trouble is not known The maximum voltage developed during track does not exceed the rating as given by the manufacturer, and the tachometer is connected to the grid of a tube through 680,000 ohms, which fact thereby eliminates the possibility of a current overload This trouble will be investigated further, and an effort will be made to correct it A new component may be required

DME TEST EQUIPMENT

General

A brief discussion of recent test equipment is included because this equipment and its related procedures are as important as the DME itself to satisfactory operation

Track Simulator

It was recognized that there was a need for a device which would simulate a transponder and an aircraft in flight Since the interrogator is stationary during bench testing, it was necessary to produce two r-f reply pulses of the correct spacing and frequency and to increase or decrease progressively the time delay between the interrogation pulses and the reply pulses

An r-f signal generator was available to provide the necessary r-f pulses with a manual delay control The delay was varied by manually positioning a delay multivibrator potentiometer The signal generator has been modified by adding a switch and a microphone jack The switch disconnects the signal-generator potentiometer, and the jack places the simulator potentiometers in series with the signal-generator potentiometer In this way tracking may be accomplished at any working distance

The tracking simulator uses a 5000-rpm, 400-cps motor generator to drive the track-simulator potentiometers, which are in series with the manual potentiometer of the signal generator A gear reducer with a ratio of 10,000 to 1 is used between the motor generator and the track-simulator potentiometers The tracking speed may be varied over a range of about 100 to 400 miles per hour (mph) Five 10,000-ohm potentiometers in series are used in the track simulator to reduce the signal-generator delay jitter The generator is connected to a microammeter which indicates the motor speed This is a rough indication of the tracking speed However, since the multivibrator delay does not increase linearly with resistance, the meter cannot be read directly in mph In order to secure tracking speed, the time needed by the DME distance indicator for a one- or ten-mile course is established, and the measured time is converted to mph

Since the simulator potentiometers are discontinuous, the front panel is provided with a dial light which is turned on when the wipers are not making contact This simulator has proved to be very useful because it permits tracking in the laboratory where full test equipment is available It is economical because it eliminates the necessity of test flights when routine tracking is desired Figs 24 and 25 show the track simulator

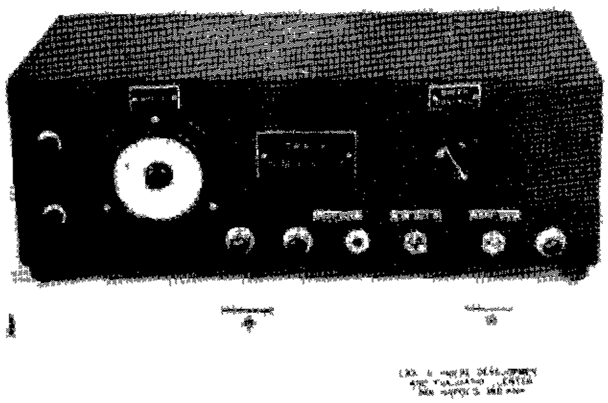

Fig 24 Exterior View of Track Simulator

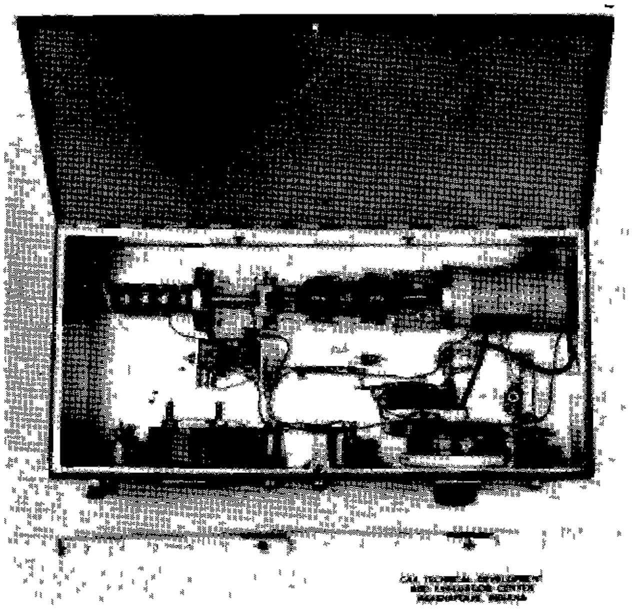

Fig 25 Interior View of Track Simulator

DuMont Oscillograph Type 256-D

This oscillograph has been modified so that the markers and video may be viewed simultaneously The purpose of this change was to provide a means of accurately positioning the delay-line coils The marker-oscillator crystal was changed to 142 8571 kc so that seven-microsecond markers would be available This eliminates the necessity of interpolating between markers or of relying upon a linear-sweep dial calibration All delay-line coils of the FTL Model DIA at this Center have been adjusted to use this modified oscillograph

Standard Federal Airways Test Rack

There has been received a new test rack which should include the following major units

- Pulse counter
- Wavemeter and power detector
- Oscilloscope
- UHF signal generator
- Video pulse generator
- Directional coupler

To date, the signal and pulse generators have not been received The pulse counter, wavemeter, oscilloscope, and directional coupler have been used with very satisfactory results The wavemeter has a very sharp response and is very convenient to use Sufficient testing has not been accomplished to permit comment concerning the accuracy of the equipment received

CONCLUSIONS

On the basis of the bench and flight testing performed at this Center, the conclusion is reached that the FTL Model DIA interrogator represents a substantial advancement in airborne DME It is reasonable to assume that this interrogator, with a few modifications, would be entirely suitable as production equipment for general use It is believed that the modifications described have improved its reliability Several of these modifications have been incorporated into DIA interrogators which are being evaluated by commercial airlines flying the New York to Chicago airway, which has full DME ground implementation The modifications were not intended to represent the ultimate improvement possible but were made to obtain the most reliable operation in the shortest time with the means available The difficulties experienced are presented in an effort to localize the defects in the developmental equipment prior to production

The problem of standardizing pulse spacings will require a standardization of test procedures, and it is believed that precision oscilloscopes with seven-microsecond, crystal-controlled markers are adequate to satisfy the system requirements Additional facts concerning this problem will be revealed as system testing is intensified

Transmitter-frequency standardization will require further investigation The accuracy of present test equipment is hardly adequate It is believed that more accurate frequency-measuring equipment will be required for interrogators using afc or temperature-controlled transmitters Improved afc circuitry may be required

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