Improvements to DME Interrogators and Development of Accessories

by

Warren E. Haworth

Electronics Division

TECHNICAL DEVELOPMENT REPORT NO. 296

CIVIL AERONAUTICS ADMINISTRATION

TECHNICAL DEVELOPMENT CENTER

INDIANAPOLIS, INDIANA

January 1957

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, Secretary

CIVIL AERONAUTICS ADMINISTRATION
James T. Pyle, Administrator
D. M. Stuart, Director, Technical Development Center

TABLE OF CONTENTS

IMPROVEMENTS TO DME INTERROGATORS AND DEVELOPMENT OF ACCESSORIES*

SUMMARY

This report describes a number of design improvements to DME interrogators which have led to increased reliability, greater utilization, improved performance, and lower initial installation and maintenance costs. Several special devices are described which were developed as DME accessories, including the field-strength recorder, orbit meter, and range servo.

INTRODUCTION

Development of distance-measuring equipment (DME) was retarded seriously during the first few years following its inception because of lack of agreement on various system characteristics. In the process of resolving these differences, a number of major changes were made to earlier systems, and in each case acceptance of the modified system resulted in obsolescence of earlier developmental equipments. Fortunately, late in 1949 when mutual agreement was reached on the existing requirements and parameters, no major production effort had been initiated on any of the earlier systems. Adoption of the new characteristics required full exploitation of two techniques used separately but never together in the earlier systems: (1) narrow-band, high-stability techniques, and (2) pulse-multiplex spacing.

The current system provides for 100 independent, noninterfering DME channels. These are obtained through the use of 10 interrogation frequencies located between 963.5 and 986.0 megacycles (Mc) at 2.5-Mc intervals, and 10 reply frequencies located between 1188.5 and 1211.0 Mc, with the same separation. Full crossbanding of the interrogation and reply frequencies provides the 100 discrete combinations required for 100 operating channels. It is obvious that unless steps are taken to prevent it, this crossbanding permits needless interrogation of transponders in which an individual aircraft has no interest; that is, transponders other than the one from which the particular interrogator currently is receiving service. Although no misinformation will be received by the aircraft as a result of these misguided interrogations because the frequency of reply from all except the applicable transponder will be incorrect, the needless interrogations raise the duty cycle of the other transponders and lead to a reduction in their efficiency.

It is obvious also that the receiver of any single interrogator will receive not only the reply signals from its parent transponder but reply signals transmitted by all other transponders operating at the same reply frequency as well. Again, protection from misinformation is afforded in that only the particular set of replies intended for the aircraft is returning in synchronism with the outgoing interrogations, because the crossband-channeling method prohibits interrogation of the common reply-frequency transponders. If large numbers of aircraft are flying within the confines of the system, however, the number of spurious reply pulses is likely to reach a level which will prevent proper operation of the interrogator's search and tracking circuits.

To minimize the probability of such occurrences, the DME systems employ pulse multiplex spacing. Each individual interrogation and reply signal consists of a pulse pair, with the separation between the two pulses assigned channelwise in such a way that no channels sharing a common frequency share the same pulse separation, either on interrogation or on reply. A total of 10 different pulse spacings, ranging from 14 to 77 microseconds in steps of 7 microseconds, are employed to accomplish this separation. For any given channel, the interrogation-pulse spacing differs from the reply-pulse spacing, and the sum of the two is always 91 microseconds. Each of the 10 combinations of reply- and interrogation-pulse spacings is known as a mode. Thus, a given channel may be specified by its interrogation frequency, its reply frequency, and its mode. No two channels of the 100 channels share more than one of these three parameters.

---

*Manuscript submitted for publication October 1956.

Fig. 1 Model DIB Interrogator

The requirement for 2.5-Mc channel separation dictated the design of high-stability transmitters and receivers in both ground and airborne equipment. Crystal-controlled receivers were employed in earlier DME systems; consequently, no basically new development was required. On the other hand, earlier transmitters of high-stability design made use of automatic frequency-control techniques, with correction applied in the form of automatic mechanical retuning of the transmitter-output cavity. When properly adjusted, the frequency control of these units was adequate to provide stability within system specifications (±400 kc for airborne transmitters and ±200 kc for ground transmitters). Frequent readjustments were required, however, and on a long term basis the stability requirements generally were not met.

The answer to the problem appeared to lie in development of a direct crystal-controlled transmitter or master-oscillator, power-amplifier-type transmitter. No such transmitter had been developed for DME application in 1950. The most serious handicap to such a development was the lack of tubes suitable for operation as power amplifiers at the DME frequencies.

The most significant recent developments in the field of airborne DME are the Models DIB,[1] DIC,[2] and DID interrogators, shown in Figs. 1, 2, and 3, respectively. The latter two equipments are being manufactured on a production basis and are commercially available. Development of both the Models DIB and DIC interrogators was sponsored by the Air Navigation Development Board. The Model DID interrogator is an advanced version of the DIB interrogator, and it was produced for the CAA Office of Federal Airways by Hazeltine Electronics Corporation, development contractor for the Model DIB equipment. The Model DIC interrogator was developed by the National Aeronautical Corporation. These developments have provided airborne units which represent tremendous advantages over earlier equipments. Specifically, the weight of equipment and the number of tubes and components roughly have been halved, and reliability has been greatly increased. These advances have been made as a result of increased simplicity of design, recent tube and component developments, and moderate reduction in performance requirements.

ACCESSORY DEVELOPMENTS

DME Range Servo, Model 2.

Among the requirements which were relaxed in preparing specifications for the lightweight DME interrogators was that distance information be provided in terms of the displacement of a rotating shaft (mechanical ranging units). Although a number of earlier

---

[1] C. C. Trout and W. E. Haworth, "Development of a Lightweight Distance-Measuring Interrogator, Part I, The Model DIB Interrogator," CAA Technical Development Report No. 228, December 1956.

[2] C. C. Trout, "Development of a Lightweight Distance-Measuring Interrogator, Part II, The Model DIC Interrogator," CAA Technical Development Report No. 292, January 1957.

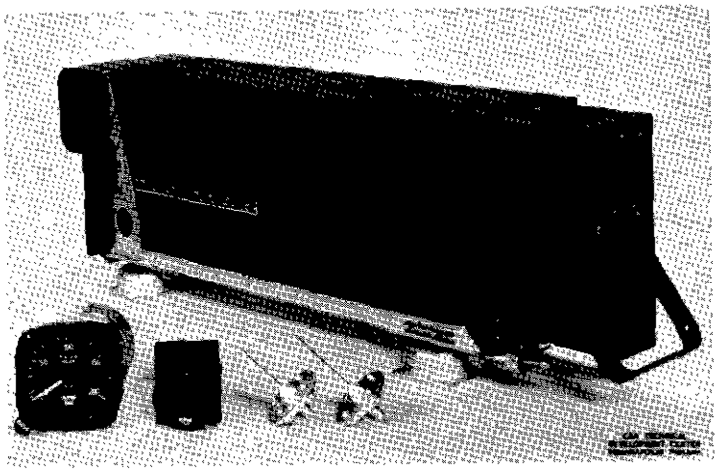

Fig. 2 Model DIC Interrogator

interrogators provided this type of indication, the circuit requirements for instrumentation of this kind were not considered justified by the almost negligible increase in accuracy obtained. This position subsequently has been justified by the demonstration of orders of accuracy by lightweight interrogators employing simple, all electronic ranging equal to or exceeding that required by operational procedures. A byproduct of the mechanical ranging units, however, is their inherent ability to provide input information to pictorial displays and course-line computers of present design. These existing computers require a DME with a potentiometer, the tap of which rotates once for each excursion of the distance from zero to maximum range.

Because it was believed that the majority of DME users would not be equipped with pictorial displays or course-line computers, and because the increase in accuracy of the mechanical ranging unit is not significant, the lightweight DME specifications permitted use of the simpler and less expensive electronic-ranging unit. The philosophy in this decision was that only those users who desired the pictorial display or course-line computer should be required to purchase and install the mechanical circuitry required to provide the proper translation between DME output and computer or display input. Furthermore, it is believed that the ultimate design of computing or display devices will and should be such that simple dc current or voltage information can be taken directly from the DME. The inconsistencies between existing interrogators and computers or displays are due to parallel development, with no opportunity

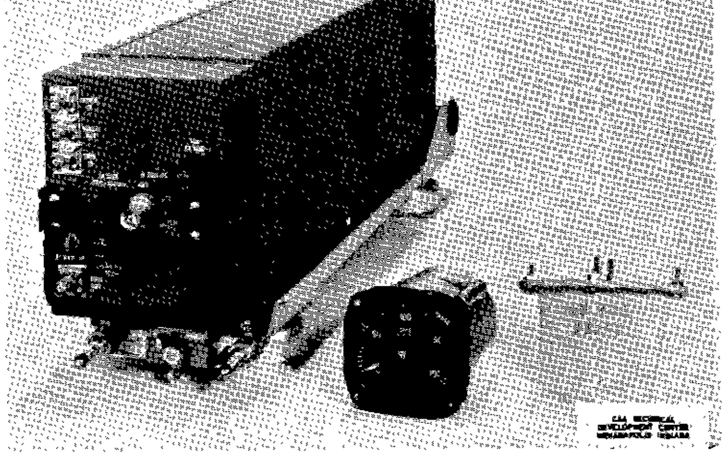

Fig. 3 Model DID Interrogator

Fig. 4 DME Range Servo, Model 2

for standardization of inputs and outputs. Obviously, because the computers or displays must contain an electromechanically driven shaft as a function of distance, there is no reason why this shaft cannot be controlled directly from the interrogator rather than via a series path through a second but fundamentally redundant servomechanism. This technique not only will result in savings in weight, space, and cost, but the order of accuracy should be increased because of elimination of an extra source of error.

In order to add computer driving capability to the Models DIC or DID interrogators for use with existing computers, simple servomechanisms were developed which were designated CAA Range Servo Models 1 and 2. Model 1 was developed previously for use with the Model DIB interrogator, and it is described elsewhere.[3] Model 2 is illustrated in Fig. 4. A schematic diagram of the Model 2 servo is shown in Fig. 5. As shown in this figure, the dc range voltage from the interrogator is referenced to a battery and converted to ac voltage by a chopper at the input of the range servo. The voltage across the computer resistor in the Model DID interrogator is the same for a given distance, without regard to the channel to which the interrogator is tuned. The voltage at each end of this resistor, with reference to the ground or any other point, however, varies with the mode to which the interrogator is tuned.[4] Thus, it is necessary to reference the computer output to a voltage which also is floating in order that the mode error will not be introduced into the range servo. The chopper output is amplified and applied to a magnetic amplifier which in turn drives a two-phase induction motor. The shaft of the motor is coupled through a gear reduction train to a two-gang potentiometer. One potentiometer section controls the feedback for the servo, and the other section provides output for the computer.

Also shown in Fig. 4 are two synchros coupled to the gear train to provide outputs for driving a Veeder counter-type indicator such as is shown in Fig. 6. Some instability was noted in the original servo because the gears in the gear train were not tightly meshed. The gear train was reworked, and the system then operated properly. More recent range servos use a redesigned gear assembly requiring only two gears.

---

[3] Trout and Haworth, op. cit.

[4] Ibid.

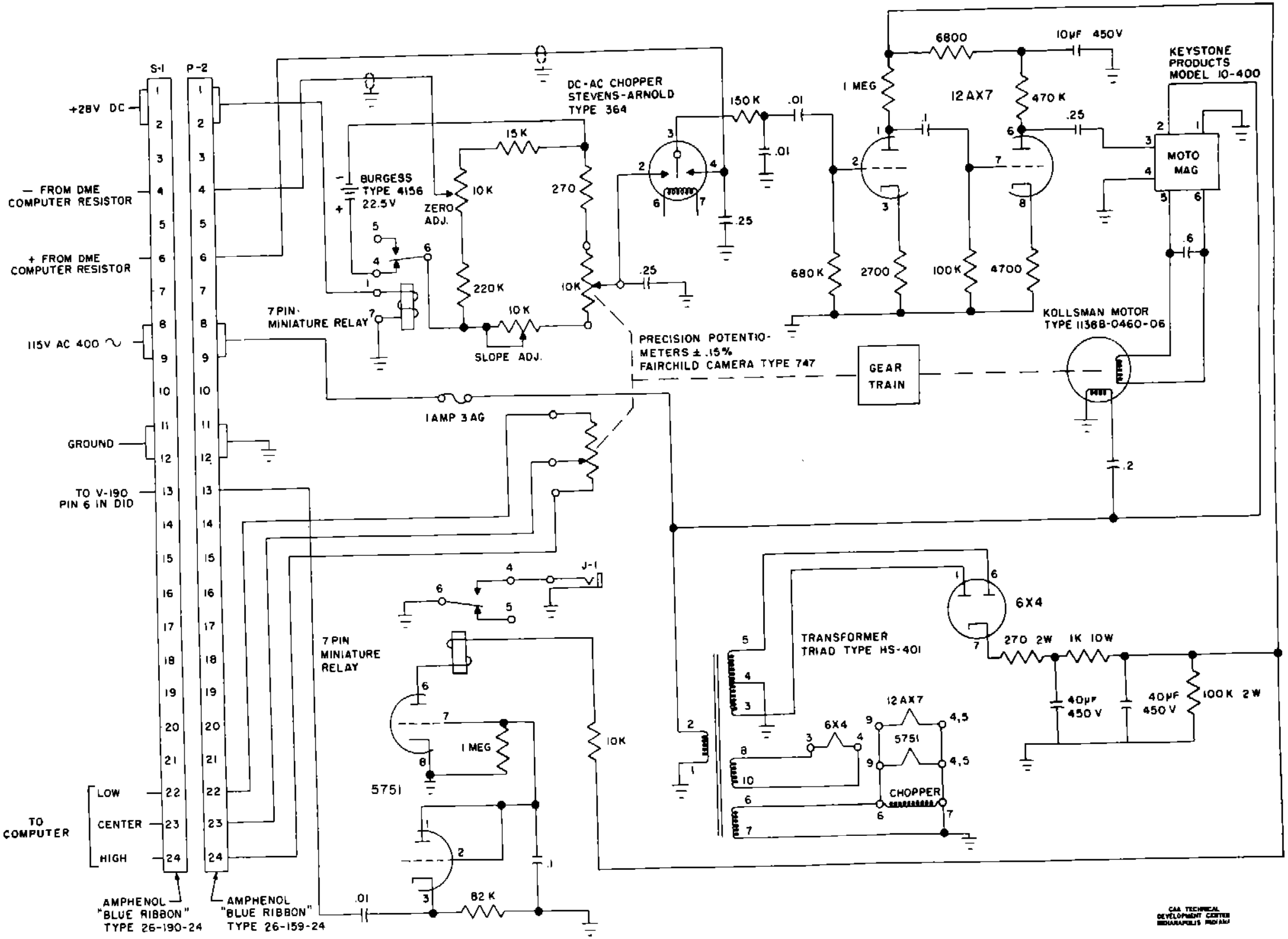

Fig. 5 Electrical Schematic for DME Range Servo, Model 2

Fig. 6 Veeder Counter Indicator

Another feature incorporated in the range servo is a relay controlled by the second pulse-coincidence tube in the Model DID interrogator. The output of this coincidence tube is fed to one cathode of the Type 5751 tube in the range servo. This half of the tube rectifies the signal and applies it as bias to the other half of the tube. A miniature relay is connected in the plate circuit of the second half of the tube, and the relay contacts are connected to a phone jack on the front panel of the servo unit. When the interrogator is receiving a properly decoded reply, the relay tube is biased to cut off, the relay is not energized, and its contacts close. This circuit is not required for computer operation, but it is used as a means of observing the action of the memory circuit in the interrogator because the period from the time the relay is energized until the set goes into search is the memory time. An external lamp connected to the relay contacts can be used to give an indication of the memory time. The action is identical to that of the signal lamp provided in some of the earlier DME interrogators.

The Field-Strength Recorder/Orbit Meter.

The field-strength recorder/orbit meter is shown in Fig. 7. The two circuits were constructed as a unit to take advantage of a common power supply. Either the field-strength recorder or the orbit meter can be constructed separately, however.

The field-strength recorder was developed to make possible the use of the Model DID interrogator for recording field-strength patterns of DME ground installations. Because the

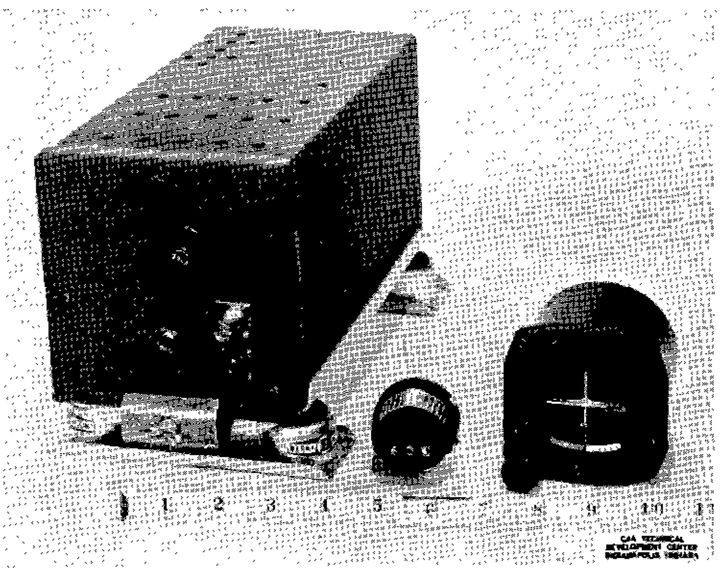

Fig. 7 Field-Strength Recorder/Orbit Meter

interrogator does not have an automatic gain control circuit, it was necessary to add an external circuit which would produce the needed voltage for recording.

Two basically different circuits were tested. The first circuit employed a motor-driven potentiometer with a feedback arrangement for controlling the gain of the video amplifiers in the interrogator. The motor was controlled by a relay operated by an output pulse from the second pulse-coincidence tube in the interrogator. Depending upon the direction of rotation of the motor, the gain of the video stages was increased or decreased. When the motor turned the potentiometer so as to reduce the gain of the receiver to the point of no output at the second pulse-coincidence tube, the relay reversed the motor rotation and the gain of the receiver again was increased. This started the sequence again. This system was very simple and required only one tube; however, because of the "no signal" part of the cycle, the memory of the interrogator slowly was destroyed and the set would unlock from the station.

A second method, employing a gated amplifier, proved to be successful. As shown in Fig. 8, the amplifier stage V_2 is fed two signals; one is the video taken from the "video out" jack on the front panel of the interrogator, and the other signal is a gate pulse which must be brought out from within the interrogator. The gate occurs at the time of the first video pulse, and it is called the track gate. The output of this amplifier consists of the first video pulse superimposed on the gate pulse. The technique of gating the first video pulse only was used to minimize random noise and unsynchronized replies.

The output of this gated stage is passed through V_1B and applied to a diode-connected triode V_3A where the track gate is removed from the video pulse. The point of clipping is controlled by the one-megohm potentiometer in the cathode circuit of V_3A. The video pulse then is stretched and amplified in V_4 and V_3B to V_5A. This bias controls the current flowing through V_5A, and putting a 5-milliampere recorder in the cathode circuit of this tube causes the recorder to reproduce the input signal.

A coaxial line is connected between the "video out" jack on the front panel of the interrogator to a jack on the panel of the recorder unit. All other interconnections are made through the rear connectors of the respective units.

Some difficulty was experienced in transporting the gate pulse from the interrogator to the recording unit. The track gate in the interrogator occurred at the proper time, and it was of correct polarity for the needed gate pulse. Any connection made to the interrogator circuit to extract the track gate, however, upset the tracking capabilities of the interrogator and caused malfunction. An attempt then was made to bring out the screen-grid pulse from the range-delay phantastron. This pulse is the one used to generate the track gate in the interrogator. This pulse was differentiated and the trailing edge of it was used for the gate pulse. This technique proved to be superior to the first method, but the length of the wire carrying the pulse from the interrogator to the recorder unit was critical. To eliminate this condition, a cathode-follower stage was added to the interrogator circuitry. A small subchassis containing the cathode-follower stage was mounted in the interrogator.

The screen-grid pulse of V-130 in the Model DID interrogator is fed to the grid of the cathode follower. The follower output then is fed to the shockmount connector and through external wiring to the in-flight recorder. At the grid of V_1A in the recorder unit, the pulse is differentiated and the negative portion is amplified and applied to V_2 as the gating pulse.

Data taken with the field-strength recorder are shown in Figs. 9, 10, and 11. Figure 9 is a horizontal field pattern of the Brownsburg, Indiana, DME ground station at a radius of 20 miles and an altitude of 1500 feet above ground. Figure 10 is a plot of the pattern, in microvolts. Figure 11 shows a section of the horizontal antenna pattern of the Dayton, Ohio, DME transponder. One arc was flown clockwise and the other counterclockwise. Both arcs were flown at 20 miles from the station at an altitude of 5000 feet. These curves illustrate the degree of repeatability which may be expected.

In obtaining data with the in-flight recorder, it is necessary first to calibrate the recorder by locking the interrogator on a simulated signal from a signal generator. The output of the generator is varied in 5- to 10-decibel steps, and the signal strength is noted on the recording paper. A typical calibration is shown in Fig. 12. It will be noted in Fig. 12 that there is a time lag between each two levels of signal. This is produced by the large filter system used on the bias voltage applied to the final tube in the recording unit. This filter was necessary to remove the inherent jitter of the video pulse. Although the recorder responds somewhat slowly, flight tests indicate that no important data are lost because of this damping effect.

Flying an orbit around a ground DME station is possible with an interrogator by watching the distance indicator and by correcting the course to maintain the aircraft at the selected distance. This method is not always sufficiently accurate, however, especially when the DME is on a long-range scale such as 0 to 200 miles. The orbit meter was developed to give the pilot a means of flying an orbit with more ease and much greater accuracy.

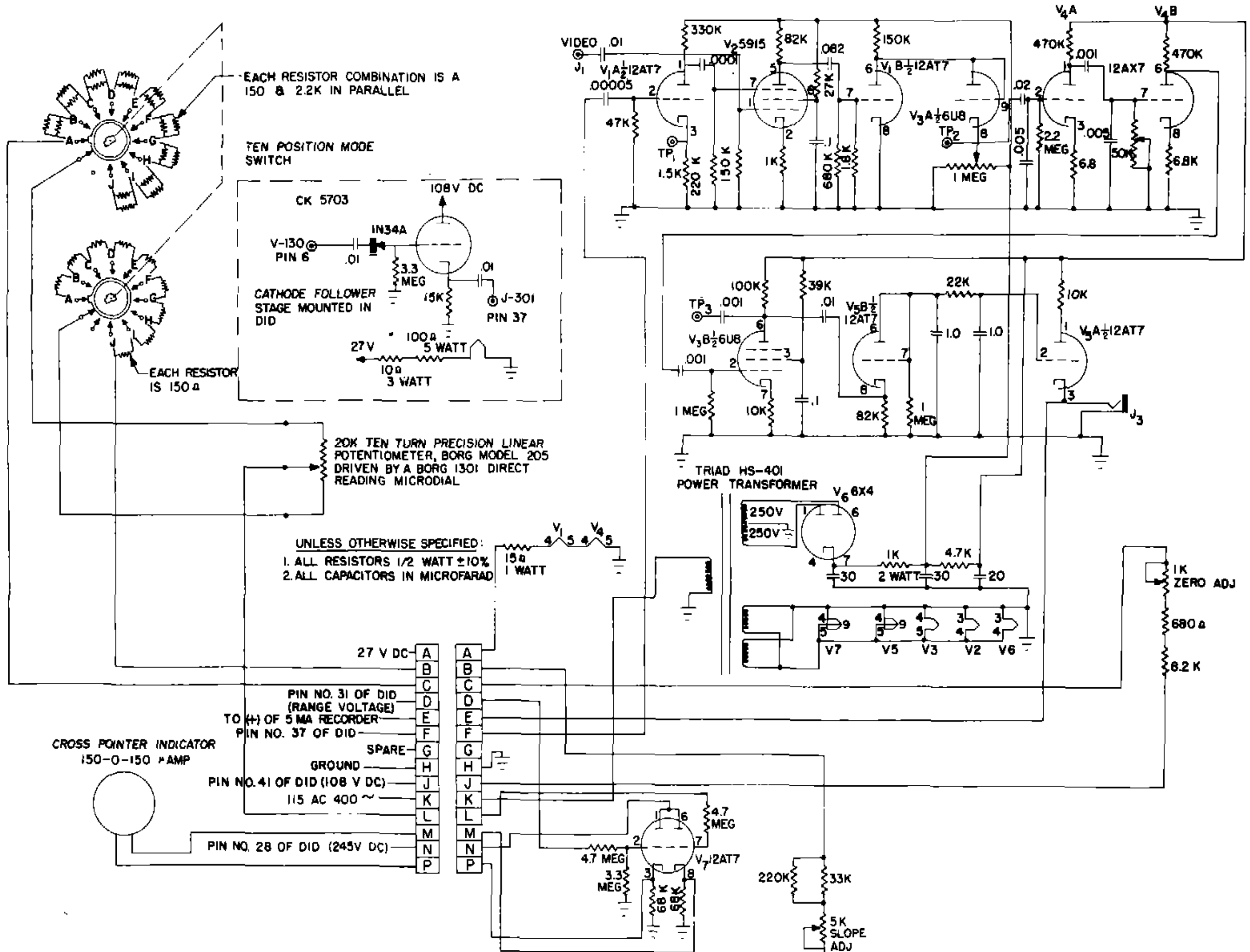

Fig. 8 Electrical Schematic for Field-Strength Recorder/Orbit Meter

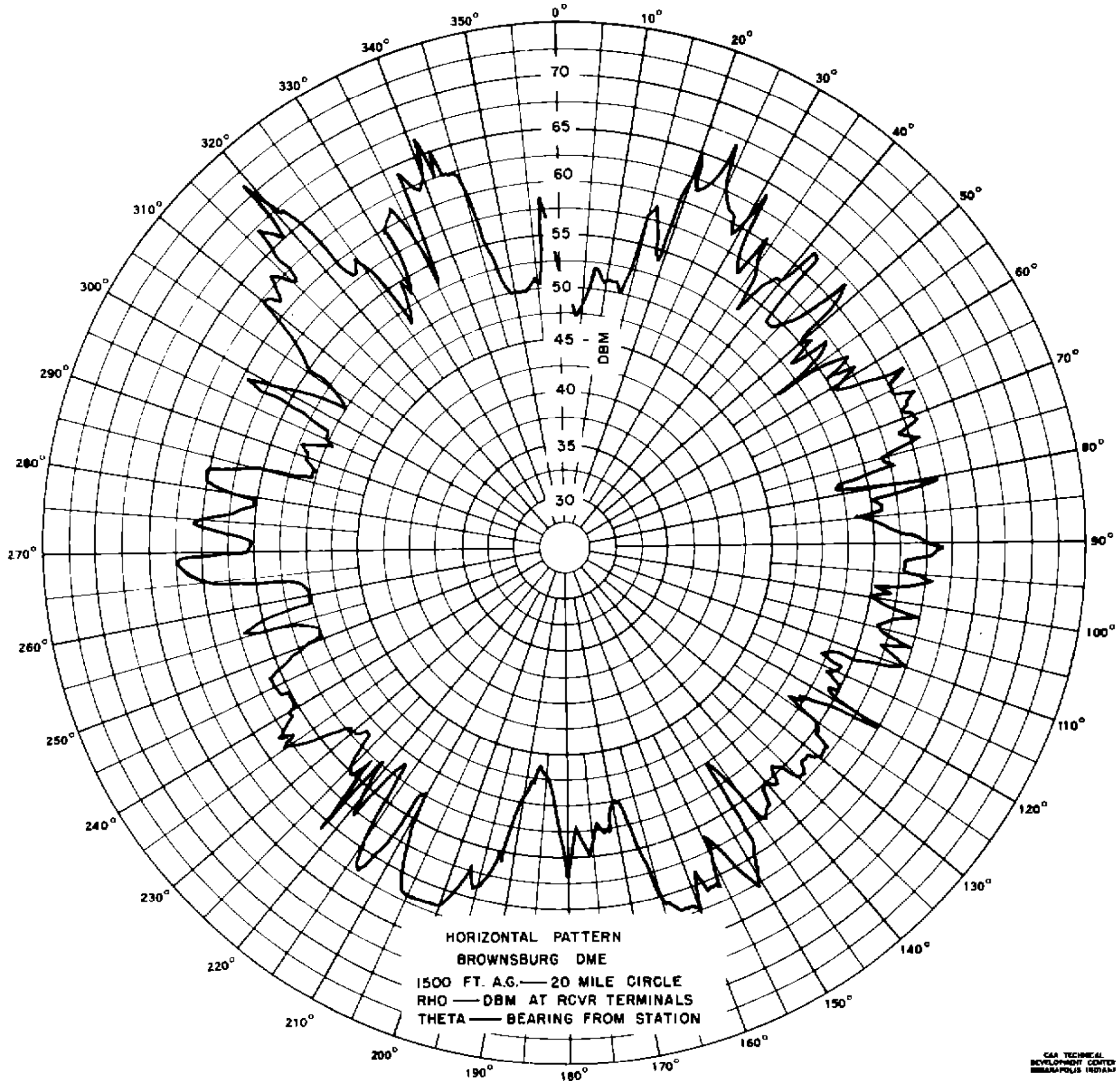

Fig. 9 Field-Strength Pattern, Brownsburg DME, in Decibels Below One Milliwatt

The basic principle of the orbit meter is the balancing of a voltage, calibrated in miles, against the range voltage from the interrogator, and displaying this balance on the crosspointer indicator. The distance selector and crosspointer indicator are shown in Fig. 7.

As shown in Fig. 8, the distance selector (direct-reading microdial) moves the wiper arm on a potentiometer and picks off a reference voltage which is fed to one grid of the double triode V_7. The range voltage from the interrogator is applied to the other grid of this tube. The crosspointer indicator is connected between the cathodes of this tube. Also shown in Fig. 8 is a ten-position mode switch which must be tuned to the proper mode for the DME channel in use. The mode switch is required to compensate for the range-voltage shift each time the interrogator is tuned to a different mode. If desired, this ten-position switch can be tuned automatically by a motor or rotary solenoid.

By addition of another tube and a small magnetic amplifier, the mode switch can be eliminated. The input of the magnetic amplifier is inserted in series with the indicator circuit

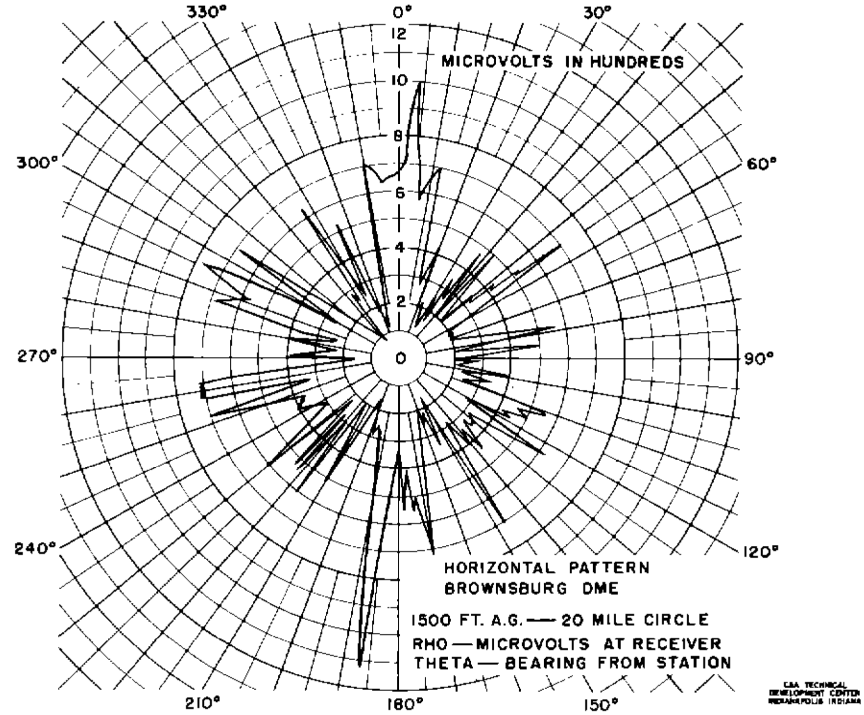

Fig. 10 Field-Strength Pattern, Brownsburg DME, in Microvolts

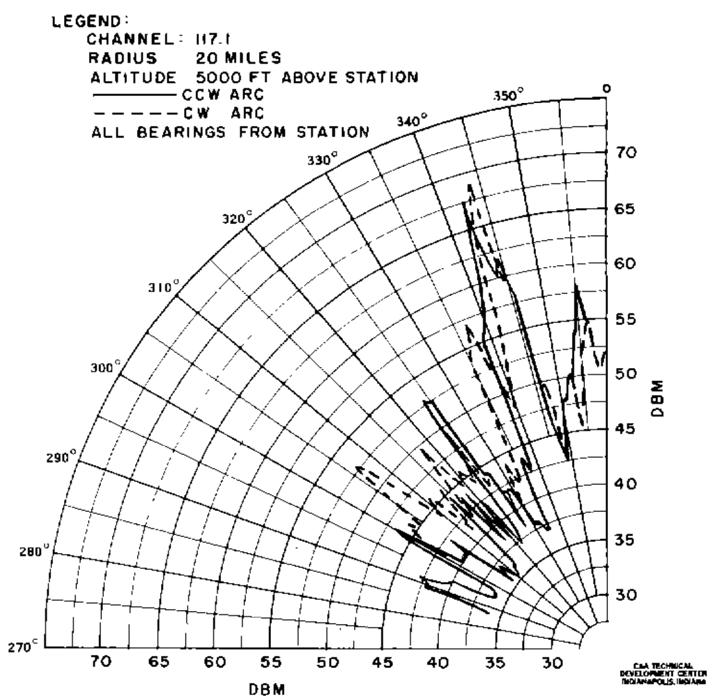

Fig. 11 Sector of Horizontal Field-Strength Pattern, Dayton DME

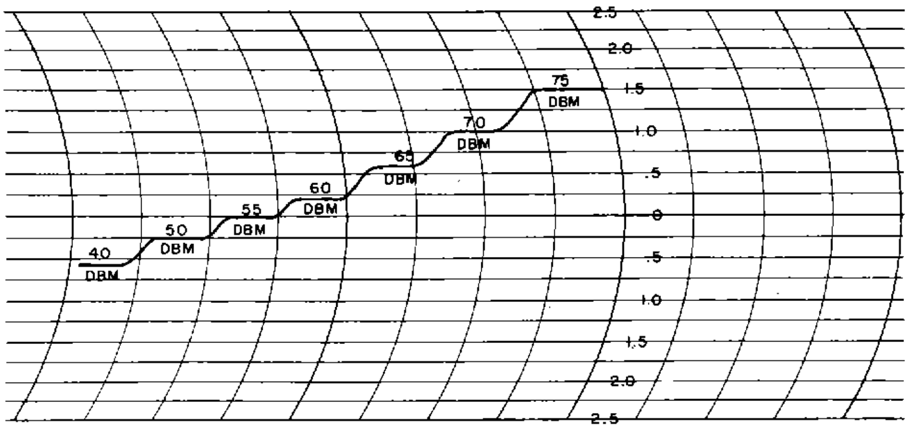

Fig. 12 Typical Recorder Calibration

of the interrogator. The voltage developed at the output of the amplifier for a given distance is the same, regardless of mode. This output then is amplified and applied to the same type of balance circuit as before. A circuit of this type is shown in Fig. 13.

The travel of the indicator needle from center to full scale (in either direction) represents about two miles. Test flights indicate that pilots can "fly the needle" easily and can readily hold the airplane within 0.2 mile through a complete orbit of the station. In a DC-3 installation, a double-pole, double-throw switch was installed to provide a means of reversing the leads to the indicator. This gives the pilot the proper sensing on the indicator for clockwise or counter-clockwise orbits so that he can always fly "to the needle" to make the proper course correction.

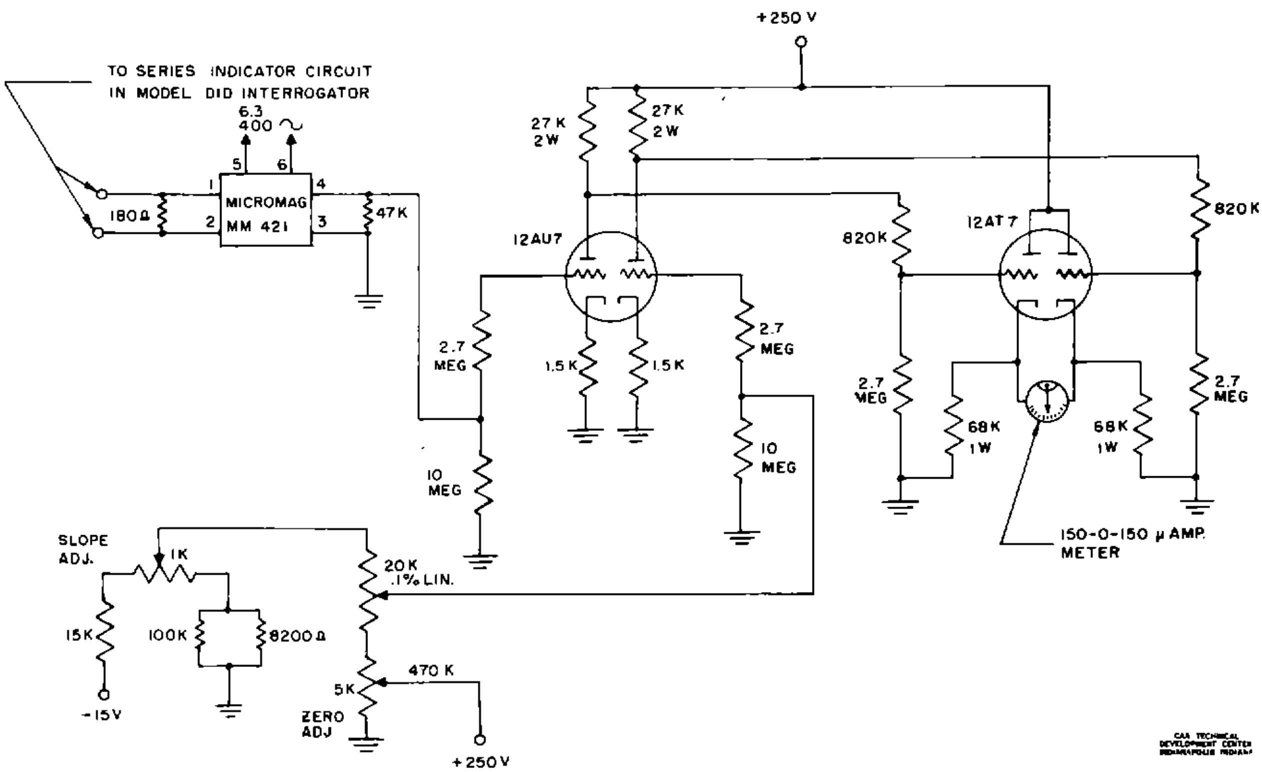

Fig. 13 Orbit Meter Using Magnetic Amplifier

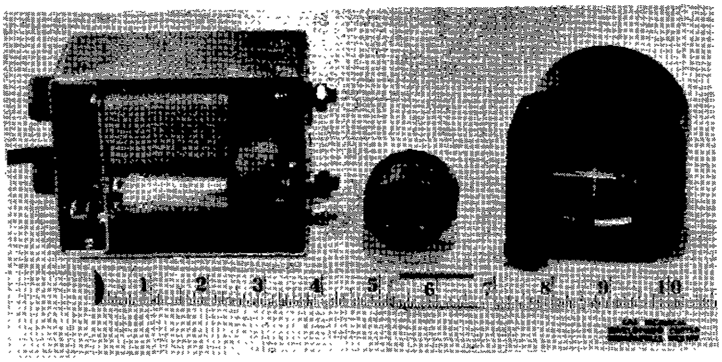

Fig. 14 Orbit Meter for Model DIC Interrogator

Another orbit meter was constructed for use with the Model DIC interrogator. This is shown in Fig. 14. The only difference between this unit and the orbit meter for the Model DID interrogator is that mode correction is not required for the Model DIC equipment. This characteristic is inherent because of design differences of the two interrogators. The orbit meter, with the exception of the magnetic-amplifier type, may obtain the required operating voltages from the interrogator to which it is connected. The orbit meter employing the magnetic amplifier requires approximately 20 milliamperes of B+ voltage which would impose an excessive drain on the interrogator's power supply.

IMPROVEMENTS

Identification Sensitivity Circuitry.

The DME system provides for identification of ground stations through periodic transmission of three-pulse rather than two-pulse replies from the transponder. Periods of three-pulse transmission are synchronized but out of phase with transmitted code identifications of the associated VOR transmitter. The spacing between the third (identity) pulse and the second (reply) pulse is held constant at 10.5 microseconds, regardless of mode (spacing between first and second reply pulses). Transmission of the identity pulse is recognized in the airborne unit by its coincidence after detection with an identity gate generated in the interrogator and having the proper delay with respect to the second reply pulse. This gate is generated every time a synchronized reply-pulse pair is received when the interrogator is in the tracking condition. Pulses received coincident in time with the identity gate will cause the coincidence tube to conduct and, in the case of the Model DID interrogator, will result in a 400-cps tone in the pilot's headset. This is the intended technique of identification. The presence of any spurious signals coincident in time with the identity gate, however, also will cause generation of the identity tone, leading to confusion.

Because of multipath replies (echoes) falling within the identity gate (see Fig. 15), an unmodified Model DID interrogator will produce a constant identification tone at close range to the ground station. Because the interrogator has two ranges, 0 to 40 and 0 to 200 miles, the circuit shown in Fig. 16 was developed to introduce gain reduction to the identity portion of the Model DID interrogator circuits on the shorter range. The large negative pulse produced at the plate of the second coincidence tube V-190 is fed back through a voltage divider to the grid

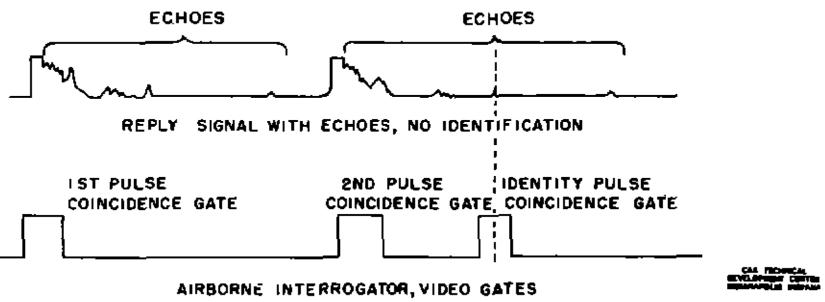

Fig. 15 Spurious Identity Response to Reply-Path Echo

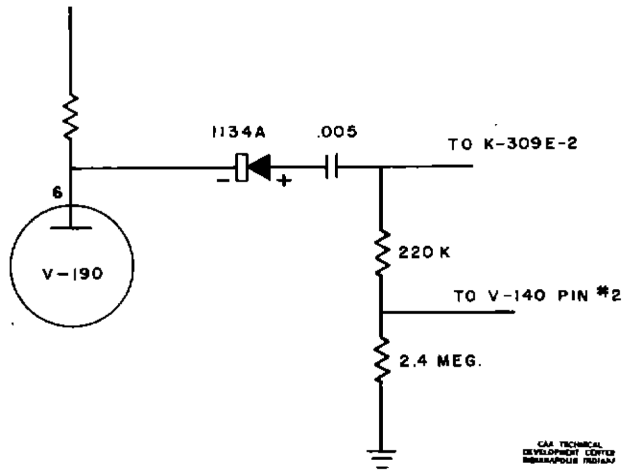

Fig. 16 Identity Sensitivity-Reduction Circuit for Model DID Interrogator

of the first video amplifier V-140. Using the component values shown in Fig. 16, the reduction in sensitivity is 17 db. Flight tests have indicated normal identity with this amount of reduction in sensitivity, even at low altitudes and flying directly over the ground station. At 5000 feet msl the identity was received to full range on the 40-mile scale. At lower altitudes the range of the identity signal, of course, is reduced. When the identity tone is lost on the short range, however, switching to the 200-mile range places the interrogator in normal identity sensitivity and the tone is present to normal ranges. To insure sensitivity standardization of interrogators using this modification, the fixed resistors R_1 and R_2 have been replaced by a potentiometer. This provides adjustment of the sensitivity to any desired level.

Spurious Radiation of the Model DID Interrogator.

In a dual installation of Model DID interrogators in a DC-3 aircraft, some difficulty was experienced in keeping the units locked on the station. This trouble was traced to radiation from the receiver of one interrogator coupled to the other interrogator by the two antennas which were about three feet apart. Because of this mutual interference, one or both sets would unlock from the ground station, even in strong signal areas.

Measurements in the laboratory revealed outputs as high as 2600 microvolts at the local oscillator frequency. Also, radiation intensities of 800 microvolts were detected on the reply frequency. Because this radiation on the reply frequency is 25 to 30 db above the minimum sensitivity of the interrogator receiver, a reply from the ground station must be quite strong to override the interference.

The antennas on the airplane were moved further apart and the installation was checked again. With one antenna on the top of the fuselage and the other at the normal belly location, no interference was observed. Another arrangement, with both antennas under the belly of the aircraft and separated by 25 feet, also provided normal DME operation. No attempt was made to find the minimum antenna separation because this would be a function of the intensity of radiation from the interrogator being used, and it would vary with each interrogator.

CONCLUSIONS

Development during the last two years has led to the availability of lightweight, reliable, accurate, and relatively economical DME interrogators. To increase usability further, three accessory units were developed: (1) the range servo for pictorial and course-line computer application; (2) the field-strength recorder for making field-strength patterns of DME ground installations; and (3) the orbit meter for accurate maintenance of preselected distances from DME stations.

To increase the reliability of the Model DID interrogator, a modification was made to the identity circuit. This change effectively reduced erroneous identity signals at close range to DME ground stations.

An investigation was made of the spurious radiation from the Model DID interrogator and its effect on other interrogators in a dual-aircraft installation.