UHF DISTANCE MEASURING EQUIPMENT FOR AIR NAVIGATION

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SUMMARY

The common civil military program for navigational aids for use on and off the airways is based on a polar coordinate system from which a pilot may obtain his position relative to a known ground location This navigational information is supplied in the form of azimuth and distance measurement from any preselected ground facility

Under this program, azimuth information is supplied by the VHF omnirange which is now being installed on a country-wide basis Development work on the final version of the other parameter of the navigation system, viz , the distance measuring equipment, is nearly completed and plans are being made to add that equipment to the VHF omnirange facilities in the near future Addition of the distance measuring equipment to the instrument landing system (ILS) to provide continuous distance information to the runway touch-down point also is contemplated

The distance measuring equipment, commonly referred to as DME, employs pulse techniques and the interrogator-transpondor or challenge-reply principle so widely used in identification equipment during World War II A portion of the frequency band, 960 - 1,215 Mc assigned to aids to air navigation, is being used for DME implementation This report describes the development of several types of DME and the results of the tests made on these systems

In operation, the aircraft unit of the DME, commonly called the interrogator, continuously transmits a train of short duration rf pulses These pulses are received at the ground station, called the transpondor, and are shaped by suitable circuits into trigger pulses, which modulate the transmitter portion of the transpondor The regenerated rf pulses transmitted by the transpondor, on a different frequency than the original received pulses, are in turn received by the airborne receiver section of the interrogator Electrical measuring circuits within the interrogator measure the time elapsed between each pulse transmitted by the interrogator and the reception of its corresponding reply pulse from the transpondor This time is directly related to the distance between the aircraft and the ground station and is converted, by suitable measuring circuits within the interrogator, into proper voltages for operating the pilot's distance indicator The indicator is calibrated directly in miles As many as 50 aircraft can use the same ground transpondor equipment simultaneously to obtain continuous distance information without interference and with no reduction in performance.

The latter part of the report covers a description of the internationally standard 100-channel DME system and the basic principles used in adopting certain characteristics. The system is in agreement with the plans outlined by the SC-31 report of RTCA and provides considerable latitude for the design of future types of air navigation and traffic control aids in the same frequency spectrum

INTRODUCTION

Many organizations have taken an active part in the development of DME Among these are the Naval Research Laboratory, Canadian Research Council, General Electric Company, Hazeltine Electronics Corporation, Federal Telecommunication Laboratories, U S Air Force, and the Civil Aeronautics Administration. The earliest operating DME was built by the Canadian Research Council in 1945, and was designed for operation in the frequency region of 200 Mc. Subsequent models of this equipment are now in continuous operation along an experimental airway between Montreal, Quebec, and Windsor, Ontario Early in 1946, an experimental DME designed for operation in the region of 1,000 Mc was completed at the Naval Research Laboratory by the Combined Research Group The primary purpose of constructing this model was to determine whether propagation in this frequency band would be suitable for DME use With this question answered in the affirmative, the U. S. Air Force awarded contracts to the Hazeltine Electronics Corporation and to the Federal Telecommunication Laboratories for the construction of development models of 1,000 Mc distance measuring equipment In the meantime, the original Naval Research Laboratory model was transferred to the CAA

Technical Development and Evaluation Center at Indianapolis for operational testing In October 1946, this model (together with early Hazeltine and Federal models) was demonstrated at Indianapolis to representatives of PICAO (Provisional International Civil Aviation Organization) Enthusiasm, occasioned by more widespread realization of DME potentialities, led to the establishment of Special Committee 21 of the Radio Technical Commission for Aeronautics The function of this committee, which met in December 1946, was to standardize DME specifications so that all future equipments, regardless of manufacturer or procuring agency, would be capable of operating as a part of a single standardized system The specification[1] prepared by SC-21 dictated the basic requirements to be met by all future equipments, but was so designed that individual variations in lesser details would be possible without rendering the individual unit incapable of operation in conjunction with other units of the system

Shortly after this specification was released, the CAA placed an order with the Hazeltine Electronics Corporation for a small number of ground transpondors and aircraft interrogators These equipments were ordered on a specification prepared at the Technical Development and Evaluation Center meeting all of the basic requirements of the RTCA standard In addition, the Navy ordered a quantity of transpondors and interrogators through the CAA to meet this same specification About the same time, the Air Force requested Hazeltine and Federal to modify the units covered by their contracts to conform, insofar as possible, to the RTCA specification Delivery of the equipments covered by both the CAA and the Air Force contracts was completed in the summer of 1948

Extensive laboratory and service tests were conducted by the Air Force and the CAA on these equipments The primary purpose of these tests was to evaluate the relative merits of two different types of DME channeling At the time of preparation of the SC-21 DME specification, the requirement existed that the DME system be capable of operation on any of 50 independent and noninterfering channels It was intended to install a DME transpondor at each VHF omnirange[2] site to provide a complete azimuth-distance ground facility There were to be 30 such omniranges within a 500 mile square, each with a discreet frequency assignment, (these 30 frequencies would be repeated in each adjacent 500 mile square, non-interference being achieved by the geographical separation) In addition, DME transpondors were to be installed at each instrument landing site, there being 20 of these for each 500 mile square, all with different frequency assignments. The means of obtaining the required 50 channels employed by Federal and the means employed by Hazeltine were different The Federal equipment provided the 50 channels by assigning discreet radio frequencies for each channel Since the DME is a two-way system and requires different frequencies for the air-to-ground and the ground-to-air transmissions, a total of 100 different radio frequencies were required In order to provide this number and remain within the assigned DME frequency band, a high stability system, wherein the individual frequencies are separated by approximately 2 4 Mc, was required The Hazeltine approach to the problem consisted of selecting 26 radio-frequencies, with adjacent spacing of 9 5 Mc, within the assigned band and repeating each frequency four times. To prevent interference between channels on the same frequency, a system of double pulse transmissions, or pulse multiplex, was employed In such a system, desired signals are selected and undesired signals rejected by proper design of video coding and decoding circuits

The tests performed by the Air Forces and the CAA were conducted under the auspices of RTCA subcommittee SC-40 (Standardization of DME Testing Procedures)[3] Both systems of channeling were found to be satisfactory, but the channeling problem became further complicated by a change in the

[1] RTCA Paper 6-47/EC-4, Report of SC-21 (Distance Measuring System Standardization), January 16, 1947

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

[3] RTCA Paper 121-48/DO-24, Report of SC-40 (DME System Characteristics), December 15, 1948

operational requirement for the number of channels to be provided by the system. Re-examination of the over-all domestic short-range navigation requirements by RTCA subcommittee SC-22 led to the decision that a total of 100 channels must be provided rather than only 50.[4] It was generally considered that extension of the Federal system to 100 channels by further sub-division of the channel spacing (from 2.4 to 1.2 Mc), if possible at all, would seriously delay the operational use of DME. Since separations of the order of 2.4 Mc had been shown to be practical, and since the pulse-multiplex method of channeling had likewise proven its worth, the decision was made by SC-40 to combine the two techniques in order to obtain the 100 channels. Tests of the pulse-multiplex system indicated that the number of times an individual frequency could be employed might well be increased from four to ten, thus, 100 channels could be provided by the use of only 20 radio frequencies (ten for interrogation and ten for reply). By employing a spacing between radio frequencies of 2.5 Mc, the entire DME system could be implemented with a band of approximately 50 Mc. Conservation of spectrum was held to be of extreme importance due to the requirements of RTCA subcommittee SC-31.[5] Among the requirements laid down by SC-31 was one prescribing that the 960 - 1,215 Mc band must ultimately be used as a frequency medium for the entire short-range navigation system including DME, omnirange, instrument landing, voice, and pictorial display.

A specification covering a system having the above channeling characteristics was prepared by SC-40. This specification was presented at the February 1949, meetings of the International Civil Aviation Organization and approved as an international DME standard. Production equipment meeting the system requirements outlined by the SC-40 specification is expected to be available in 1950.

[4] RTCA Paper 76-48/DO-17, Report of SC-22 (Pairing of localizer, glide slope, VHF omnirange, and DME frequencies), August 2, 1948.

[5] RTCA Paper 27-48/DO-12. Report of SC-31 (Air Traffic Control), May 12, 1948.

BASIC DME PRINCIPLES

In order to more clearly illustrate the fashion in which DME actually measures distance, the operation of a basic system will be described. Fig. 1 is a functional diagram of a basic DME interrogator. The Master Multivibrator, V24 and V25, generates a square wave at a repetition rate of 200 per second. The leading edge of each pulse is used to trigger the time measuring circuits as well as the aircraft transmitter. The transmitter is fired through the keyer, the modulator, and the pulse transformer. The positive waveform at the grid of the modulator discharges a delay line in the plate circuit through the voltage step-up pulse transformer. The output of the pulse transformer, approximately 1 μsec in duration, is applied to the plate of the transmitter tube which is a Type 2C39 cavity tuned triode oscillator. During this period of plate voltage application to the transmitter, the tube oscillates at a frequency determined by the tuning of the cavity. Coupling between the transmitter and the antenna is accomplished by means of a small hole in the transmitter cavity (iris coupling). The same broadbanded half-wave antenna is employed for both receiving and transmitting.

The interrogator receiver is patterned after conventional radar receivers. The received signal passes from the antenna through a TR cavity. This cavity is tuned to the incoming frequency and acts as a preselector. The signal is then mixed with the output of the local oscillator, a Type 2C46 cavity-controlled lighthouse triode. A crystal mixer is employed. The if produced is 60 Mc. Six, if stages are used with an over-all bandwidth of 10 Mc at 6 db down. The if amplifier is followed by a detector and two video amplification stages.

At the same time the transmitter is triggered, the positive square wave from the master multivibrator is applied to the suppressor grid of the linear sweep tube V-26. Application of this square wave initiates a linear decay of the plate voltage of V-26. The circuit employed to obtain this decay, or linear sweep, is a Miller Run-down circuit which is similar to the more familiar Phantastron circuit. When the voltage at the plate of V-26 has dropped to 40 volts, the pick-off diode V-27B will conduct current applying a

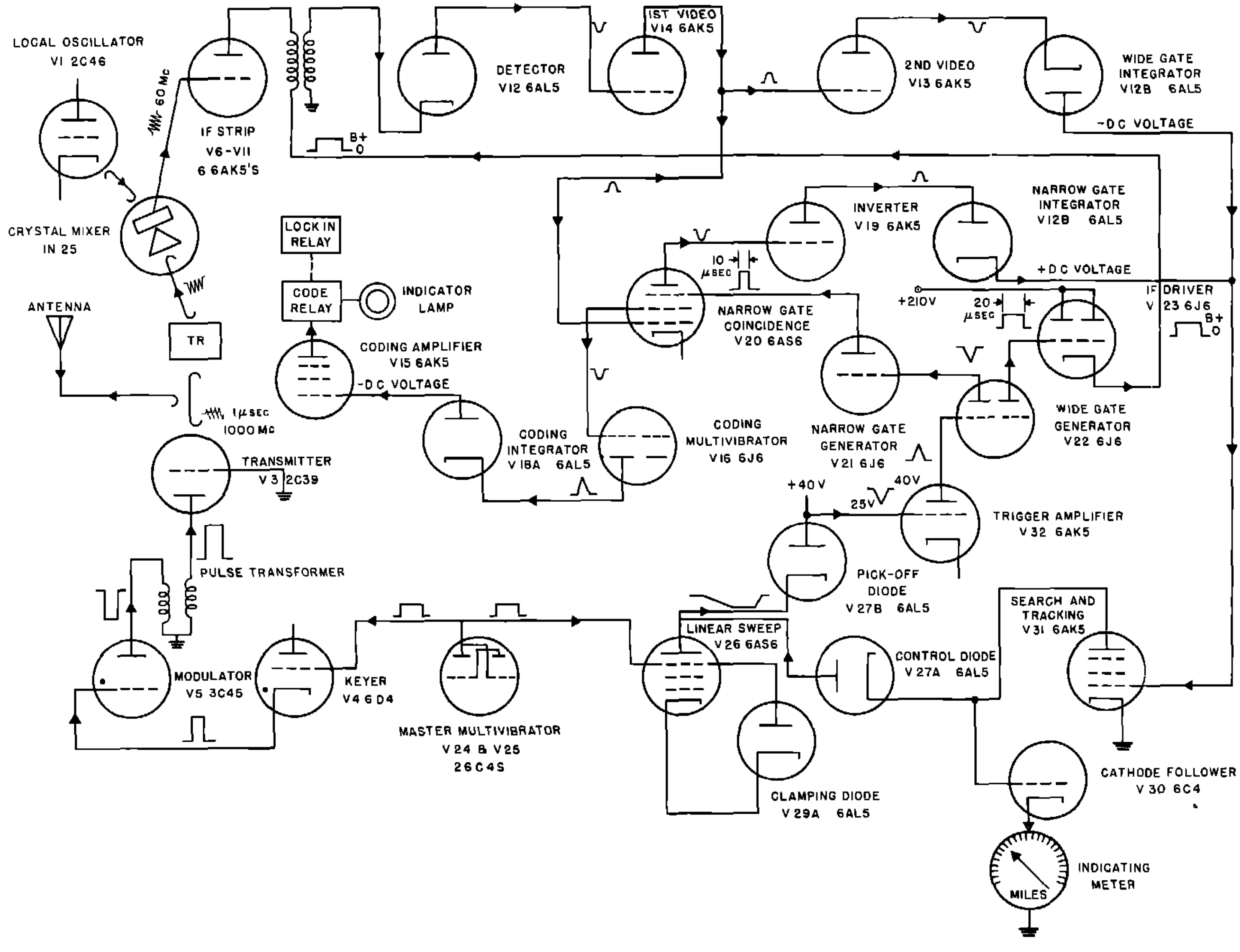


Fig 1 Experimental DME Interrogator

negative wave-front to V-32, the trigger amplifier The time required for the plate voltage of V-26 to drop to 40 volts depends upon the plate voltage existing when the tube is turned on by the master multivibrator The higher the initial plate voltage, the longer the decay or delay time The voltage on the plate of V-26 at the start of each sweep is controlled by the plate voltage of V-31, the search and tracking tube, through control diode V-27A This diode is used to decouple these two plates when the voltage at the diode plate (V-26 plate voltage) falls below the voltage at its cathode (V-31 plate voltage)

There are two phases of interrogator operation, a searching phase and a tracking phase When the equipment is first turned on, it is necessary to search in time (distance) for the transpondor reply During the searching period, the plate voltage of V-31 increases slowly from approximately 50 to 200 volts The total time required for this voltage increase is about 30 seconds In the meantime the linear sweep tube is producing 200 voltage sweeps per second, the lengths of which are slowly increasing as the plate voltage of V-31 increases As the length of this linear sweep increases, the delay between the transmitted pulse and the trigger applied to the trigger amplifier increases also

The delayed trigger, after amplification and inversion by the trigger amplifier, is used to fire the wide gate generator, a one-shot multivibrator The output of one plate of the wide gate generator is a 20 μsec square pulse of approximately 150 volts amplitude This positive voltage pulse, or so-called wide gate, is applied to the grid of the if driver, a cathode follower which supplies voltage to the if strip during the application of the wide gate to its grid The if strip is cut off at all other times A negative output is taken from the other plate of the wide gate generator and used to trigger the narrow gate generator The narrow gate generator V-21 is another one-shot multivibrator the output of which is a 10 μsec positive pulse of approximately 150 volts amplitude This gate is applied to the suppressor grid of the narrow gate coincidence tube V-20 A reply signal from a ground transpondor at the proper frequency will be accepted by the interrogator receiver and will be passed through the if strip provided that it arrives during the time that the if plate voltage is turned on, i e, during the wide gate An output is taken from the first video stage of the receiver and applied to the control grid of the narrow gate coincidence tube This means that, any signal arriving during the period of the wide gate, will reach this grid If this signal also falls within the narrow gate, a signal output will be present at the plate of V-20 The leading edges of the wide and narrow gates are coincident in time, and the coincidence tube is so designed that plate current will flow only when a positive signal is applied to both the control and suppressor grids simultaneously The output of the coincidence tube is inverted by V-19 This output will be in pulse form and is integrated through diode V-12B, the narrow gate integrator, developing essentially a direct voltage of positive polarity

The output of the second video stage (which contains all signals arriving during application of the wide gate) is also integrated, developing a direct voltage of negative polarity A single integrating condenser is common to both the wide and narrow gate integrators so that the two direct voltages are effectively combined The resultant voltage is applied to the grid of the search and tracking tube and, by controlling the plate voltage of that tube it also controls the plate voltage of the linear sweep tube, and consequently, the delay time between the transmitted pulse and the generation of the two gates If a signal is oriented in time so that the outputs of the wide and narrow gate integrators are equal, the resultant direct voltage change applied to the grid of V-31 is zero In this case there is no change in the initial plate voltage of V-26, in other words, the voltage from which the linear sweep starts remains the same, and therefore there is no change in the delay This condition would exist for aircraft orbiting around a ground station with a fixed radius If an aircraft is flying away from a ground station so that its distance to that station is increasing, the signal returned to the aircraft by that station increases in delay with respect to the interrogating pulse This means that more of the signal will appear in the wide gate than in the narrow gate, and as a result, the output of the wide gate generator will exceed the output of the narrow gate generator When this happens, a resultant negative direct voltage is applied to the grid of the search and tracking tube causing its plate voltage and the plate voltage of the linear sweep tube to rise simultaneously The time required for the plate voltage of the linear sweep tube to drop to 40 volts then is increased as a result of this higher starting voltage. The triggering of the wide and narrow gates also is delayed and both gates effectively move out in time with respect to the transmitted pulse. They will continue to do so until the return signal again is balanced between the two gates, and the narrow and wide gate integrators have equal outputs In the case of an aircraft approaching the station, the opposite occurs The narrow gate integrator output exceeds that of the wide gate, thereby applying a positive voltage to the grid of V-31, with a consequent decrease in the gate delays until the signal is again bracketed between the two gates

From the above, it may be seen that the plate voltage of V-31 is proportional to the distance between the aircraft and the ground station. This voltage drives a cathode follower, the plate current of which operates a dc milliameter calibrated directly in statute miles

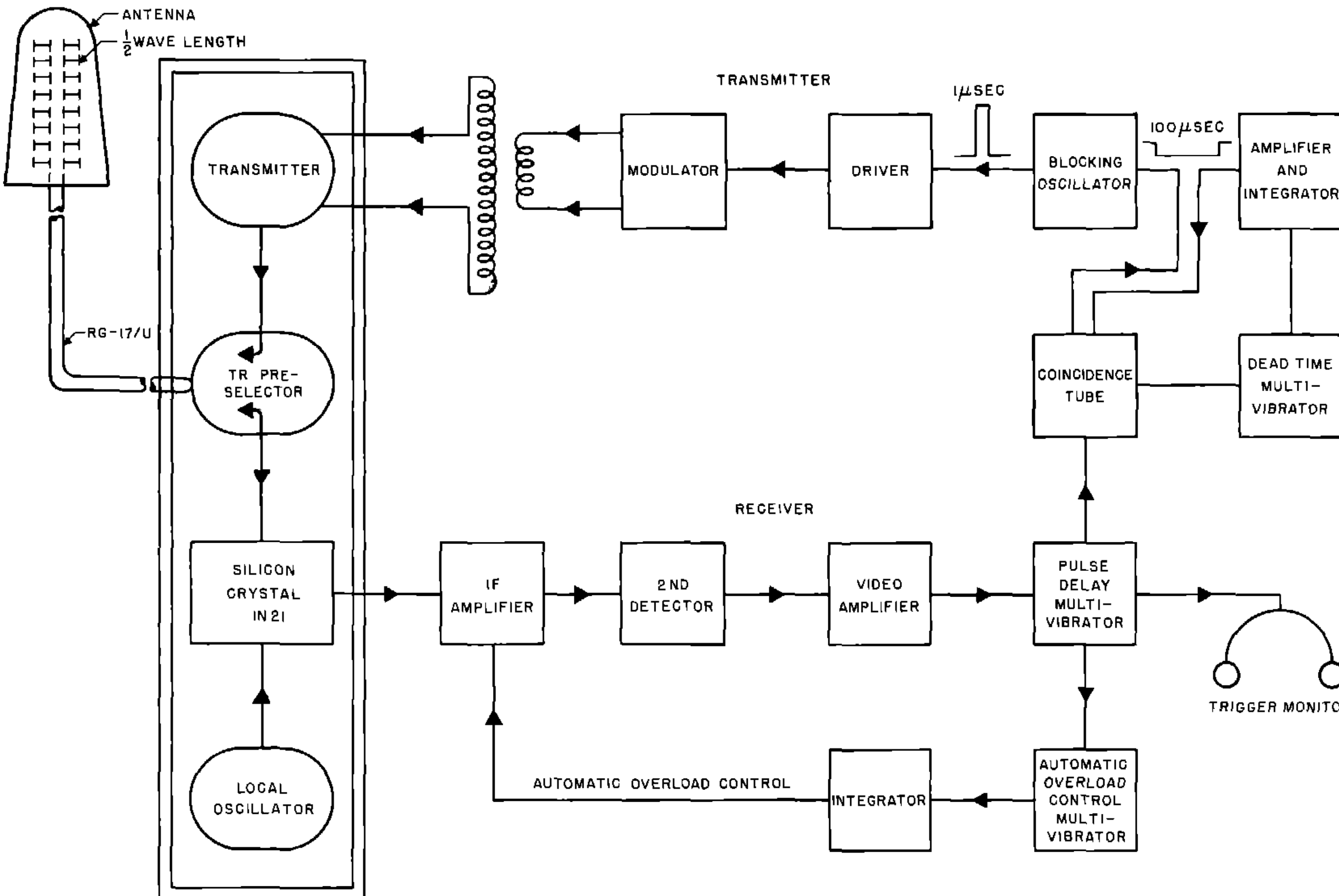
The screen grid of the narrow gate coincidence tube is purposely improperly bypassed, thereby permitting an amplified output to be taken from the screen as long as a signal appears at the control grid Thus, any signal arriving during the time of the wide gate, regardless of whether it also arrives during the time of the narrow gate, will be amplified from the control grid to the screen of this tube and will appear as a negative pulse at the screen grid This pulse triggers the coding multivibrator V-16, the output of which is integrated and applied to the grid of the coding amplifier V-15 as a negative direct voltage If this voltage is of sufficient magnitude, it will cut off the coding amplifier which is normally conducting Interruption of plate current will operate the code relay in the plate circuit of the coding amplifier When this relay operates, the ground return of the search and tracking tube grid is removed, thereby interrupting the searching operation The grid is now controlled entirely by the direct voltage outputs of the wide and narrow gate integrators Operation of the code relay also turns off the indicator light, indicating to the pilot that a signal is being received in the gates Should this signal fade, the code relay will again close, however, since the lock-in relay is now self-holding, the search and tracking tube will remain in the tracking condition This means that the distance indicator meter will continue to indicate the reading existent at the time of the signal fade When the signal again is received, provided the fade is not too long in duration (15 to 30 seconds), the indicator light will go out, and the tracking circuits will continue to follow the signal

A pushbutton is provided on the control panel to initiate the searching operation Depressing this button causes the indicator needle to drop to a zero miles reading. On release of the button, the needle will commence sweeping slowly out to a 120-mile reading until it is stopped at the proper distance by operation of the code relay, at which time the tracking circuits become effective

Two distance ranges, 0 to 12 and 0 to 120 miles, may be selected manually by the pilot Since this is a single channel DME, a special release switch is provided in the event the pilot wishes to search for a second beacon beyond the distance at which the first beacon is received

By periodically interrupting the beacon transmissions in accordance with the Morse code, the indicator light on the control panel will flash off and on, thus identifying the beacon from which the signals are being received This, of course, can be done only after a signal has been locked in the gates

Fig 2 is a block diagram of the transpondor and will be used to describe operation of that unit Signals at the proper frequency are received through a non-directional broadbanded antenna array consisting of four vertically stacked full wave horizontal radiators These signals are then fed to the if amplifier through a TR cavity and crystal mixer in the same fashion as in the interrogator receiver The if strip is identical to that employed in the interrogator with the exception that it is not gated After passing through the second detector and one stage of video amplification, the signal pulses are used to trigger a one-shot pulse delay multivibrator The purpose of this delay is to permit recovery time of the interrogator receiver and, to allow for the time required for the interrogator tracking circuits to get started This introduced delay, which is constant for all incoming pulses, is cancelled in the aircraft unit by proper adjustment of the indicating circuit



ANTENNA

1. 50 OHM
2. 4 WAVELENGTHS LONG
3. VERTICALLY POLARIZED
4. BROAD-BANDED AT 1000 Mc
5. HEIGHT - 60 FEET

RECEIVER

1. SILICON CRYSTAL DETECTOR
2. LOCAL OSCILLATOR - 2046 LIGHTHOUSE TUBE
3. 60 Mc IF 6 STAGES
4. BAND WIDTH - 6 Mc 6 db DOWN
5. SENSITIVITY - 20 MV

TRANSMITTER

1. 2-2C42 LIGHTHOUSE TUBES
2. FREQUENCY 950-1150 Mc
3. PEAK POWER - 2 KW
4. CAPACITY - 50 AIRCRAFT
5. OUTPUT - 1μ SEC PULSE

Fig 2 Experimental DME Transpondor

Three outputs are taken from the pulse delay multivibrator One of these is fed to the coincidence tube, the output of which triggers the blocking oscillator The blocking oscillator output is used to fire the transmitter through the driver and modulator The modulator, which consists of three 3D21A tubes in parallel, produces a 1 μ sec output pulse, which is stepped up by a pulse transformer in the plate circuit and applied to the transmitter The transmitter consists of two 2C42 lighthouse triodes connected in parallel in a cavity-tuned circuit The rf output of the transmitter is iris-coupled to the common receiving and transmitting antenna

In order to limit the duty cycle of the transmitter and to prevent retriggering by multipath signals, it is desirable to prevent too frequent firing of the transmitter This is accomplished by means of the dead-time multivibrator. A second output of the coincidence tube is applied to the dead-time multivibrator, triggering this tube, which in turn produces a 100 μ sec pulse After amplification and inversion, this pulse is applied back to the suppressor grid of the coincidence tube The polarity of the applied pulse is negative and the coincidence tube will not conduct as long as this pulse is present at the suppressor grid Thus, signals applied to the control grid, during the time of application of the dead-time pulse, will not pass through the tube to modulate the transmitter

A second output from the pulse delay multivibrator is used to trigger the AOC (Automatic Overload Control) multivibrator, another one-shot multivibrator The output of this tube is integrated and applied through a control diode to the control grid of the fourth if stage After integration the direct voltage developed is negative in polarity and has a magnitude determined by the number of pulses per second being received by the replier. When this value exceeds 6,000 per second, the negative voltage applied to the fourth if grid causes the gain of the if strip to be reduced The effect of this reduction in gain is, that only the 6,000 strongest interrogations will result in transpondor replies The purpose of this circuit is to act as additional limitation on the duty cycle of the replier transmitter

A third output of the pulse delay multivibrator is used to operate a headset for monitoring the received signal These same pulses also are fed through a diode integrator to operate a pilot lamp which will indicate that the beacon is being triggered when the light is on Similar circuits provide a visual indication that the transpondor is replying

Gap coding is applied externally by a code motor by suitably arranged cams, which periodically disable the transmitter by cutting off the blocking oscillator

DESCRIPTION OF EQUIPMENT

PULSE MULTIPLEX DME

The Hazeltine pulse multiplex DME provides, through use of 26 radio frequencies and four double pulse codes, a total of 52 independent operating channels It is obvious that by cross-banding the 26 radio frequencies, a total of (13 x 13) or 169 discreet frequency pairs (one frequency for interrogation and the other for reply) may be provided Furthermore, by using each of the 169 pairs with each of the four pulse codes, a total of (169 x 4) or 676 discreet operating channels may be provided However, it may be shown[6] that extension of the pulse code and crossband techniques to this extent, though achievable in theory, is unworkable on a practical basis when large numbers of aircraft are required to operate in conjunction with each transpondor of the system On the other hand, it may be shown that if each channel be identified by three parameters, viz , and interrogation frequency, a reply frequency, and a pulse code, and, if no two channels have more than one of these parameters in common, a system capable of handling 100 aircraft per transpondor is readily achievable under the worst possible traffic conditions (100 aircraft operating with each of the 50 transpondors, and with all aircraft within line of sight of all transpondors) In order to meet the above requirement, the present pulse-multiplex DME system must be limited to 52 channels

The pulse width employed in present DME systems is 1 5 μ sec In this pulse-multiplex system, a pair of pulses are transmitted as an interrogation at a rate of 30

[6]Hazeltine Electronics Corporation Report No. 2077W, "Results of Tests Performed at Hazeltine on Pulse-Multiplex Distance Measuring Equipment," March 1948

interrogations per second The spacing between the pulse pairs may be 10, 15, 20, or 25 µsec The reply pulses from the transpondor may also have any of these four spacings The combination of an interrogation spacing and a reply spacing is known as a "mode" A total of four modes are employed, which are made up of the following combinations

Mode	Interrogation Spacing	Reply Spacing
1	25 µsec	10 µsec
2	20 µsec	15 µsec
3	15 µsec	20 µsec
4	10 µsec	25 µsec

In the case of the interrogator transmitter, the pulses are generated by use of two soft-tube modulators, one of which applies the first modulating pulse to the transmitter oscillator which consists of a pair of cavity-tuned 2C42 lighthouse tubes in parallel A portion of the first modulator pulse is delayed and used to trigger the second modulator which applies the second modulating pulse to the same transmitting oscillator The required spacing between the two transmitted pulses is controlled by adjustment of this delay A block diagram of the interrogator is shown as Fig 3

A magnetostriction delay line is employed to introduce the required delay between the transmitted pulses, to code the transmission, and the same type of delay line is employed in the receiver decoding circuits in order to determine whether a received signal is a desired or undesired signal

The operation of the magnetostriction delay line is based, as the name implies, on the magnetostrictive principle Fig 4 is a view of a typical magnetostriction delay line The device consists of a ribbon or tube of

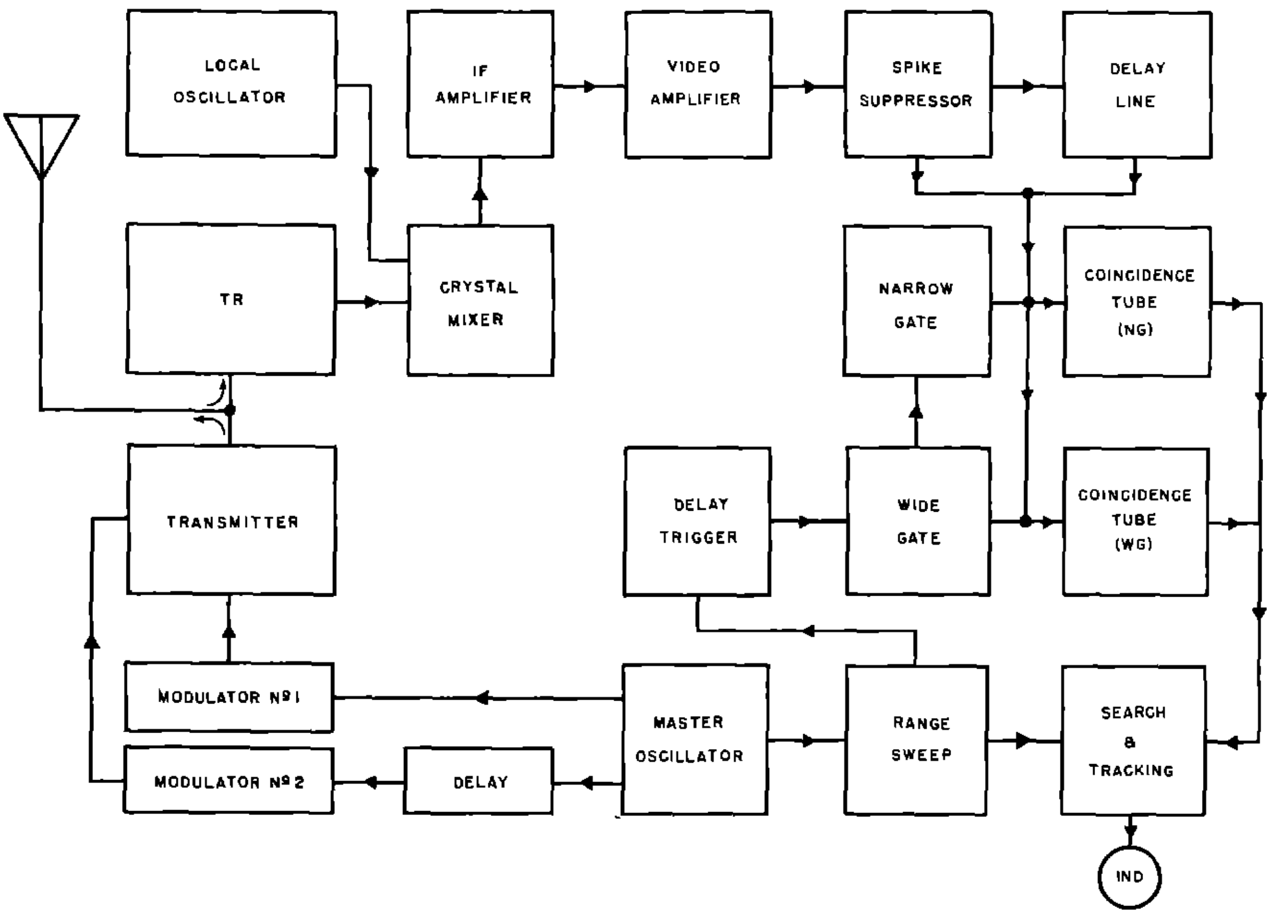


Fig 3 Block Diagram, Hazeltine DME Interrogator

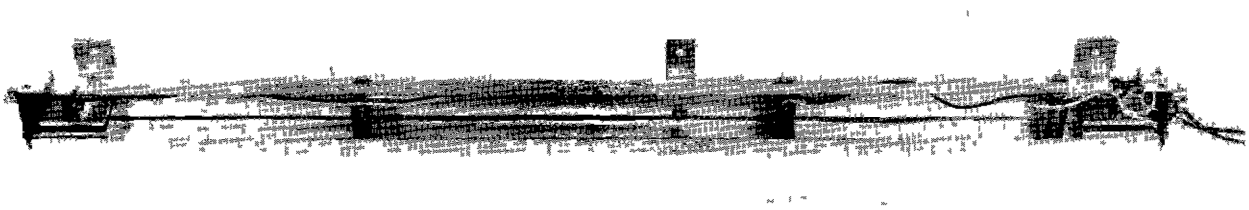


Fig 4 Magnetostriction Delay Line

magnetostrictive material (nickel has proven extremely effective) mounted at both ends and passing through the center of several small coils A pulse of current through one of these coils produces a contraction in the short portion of ribbon linked with it This contraction travels along the line at about 4 76 x 10^5 cm per second, causing a change of permeability in each section of line through which it passes As this change of permeability passes through any other coil, the change in flux results in a change in current through that coil This current change is amplified and serves as an accurately delayed pulse with respect to the pulse used to excite the nickel ribbon The spacing between the input and output coils determines the time delay which is approximately 5 38 μsec per inch of separation

Obviously the rf and if portions of the receiver will accept all radio signals at the proper frequency, including those signals made up of double pulses with incorrect spacing. The pulse-space discrimination, or decoding, is accomplished after the detection and video amplification of the incoming signal Fig 5 is a simple diagram showing how pulses of the proper spacing are accepted and pulses of improper spacing rejected All incoming signals are applied, after passing through the receiver, directly to one grid of the coincidence tube, and indirectly, through

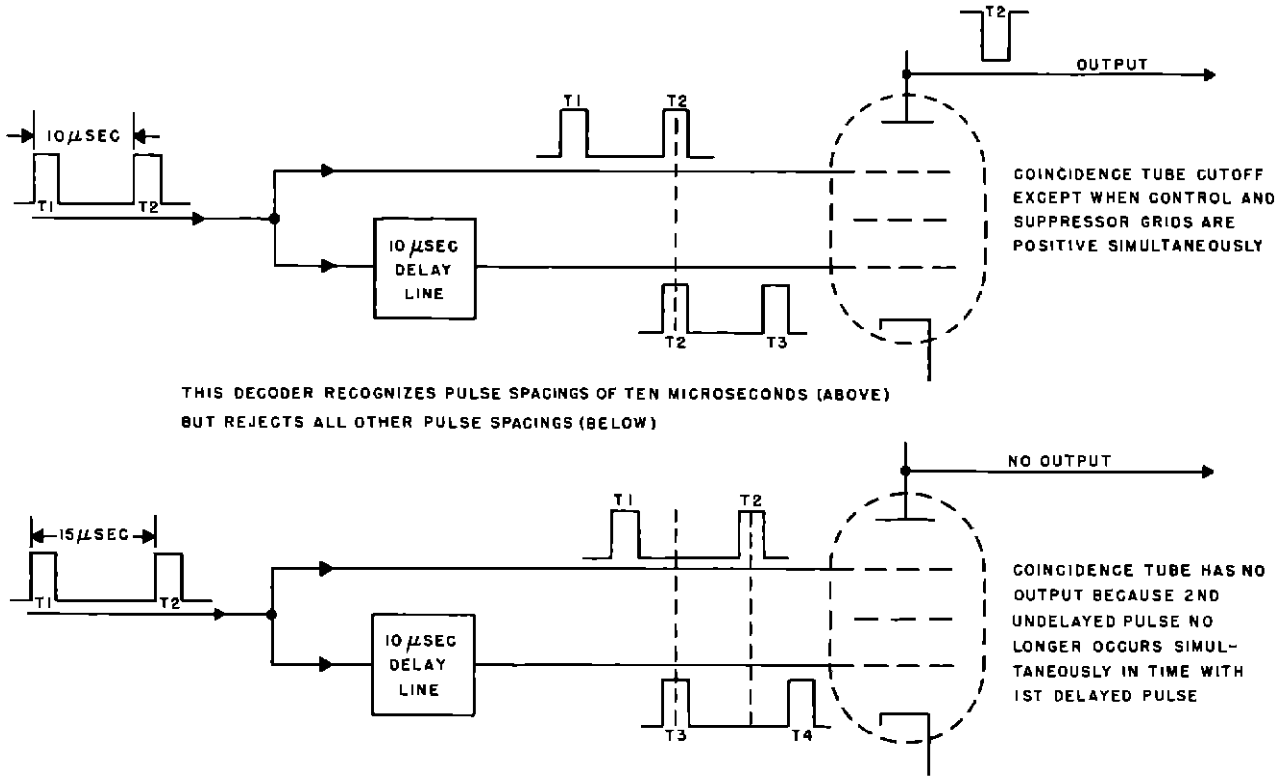


Fig 5 Decoder Operation

a properly adjusted magnetostriction delay line to a second grid of the same coincidence tube Two such coincidence tubes are actually employed, the third grid of one being controlled by the narrow gate, and the third grid of the other by the wide gate. Thus, triple coincidence must be established in each tube to produce an output, and the tubes serve useful functions in both the decoding and the tracking processes

The transmitter and receiver are tuned by remote selector switches to the desired radio frequencies The actual frequency change is accomplished by the rotation of a detent drum for each of three cavities (transmitter, local oscillator, and preselector). All three of these drums contain a row of 13 pins, each of which controls the position of a master plunger in its associated cavity when the drum is rotated, to permit that particular pin to contact the base of the plunger. The position of each drum is controlled by a selector switch on the pilot's control box as shown in Fig. 6 The local oscillator and preselector detent drums are geared together and controlled by a single switch The selector switches apply voltages to a servo-system which, in matching the applied voltage, cause the detent drums to be rotated to the proper position.

Selection of the desired mode is accomplished by a third selector switch on the control box This switch, by means of relays, selects both an output coil for coding the transmitter and an output coil for decoding purposes A single delay line is used for both coding and decoding This line employes five coils in all, one for excitation of the ribbon (either by a portion of the first transmitted pulse or by the reply signal) and four others spaced 10, 15, 20, and 25 μsec with respect to the excitation coil Use of a single delay line for both coding and decoding is made possible by an electronic switch synchronized with the transmitted pulse

The Hazeltine equipment employs a servo-driven indicating instrument of the double-pointer type. This instrument, together with the remaining units comprising the airborne installation is illustrated in Fig 6 The shaft which drives the short pointer also drives a potentiometer, the center tap of which produces a voltage proportional to distance This voltage is balanced against an electronic range voltage generated within the interrogator proper (in a similar fashion to that previously described) by means of a servo-system, the output of which drives the indicating instrument

The design of the Hazeltine DME approaches fully automatic operation in that the only functions to be performed by the pilot consist of application of power to the equipment, and selection of the proper operating

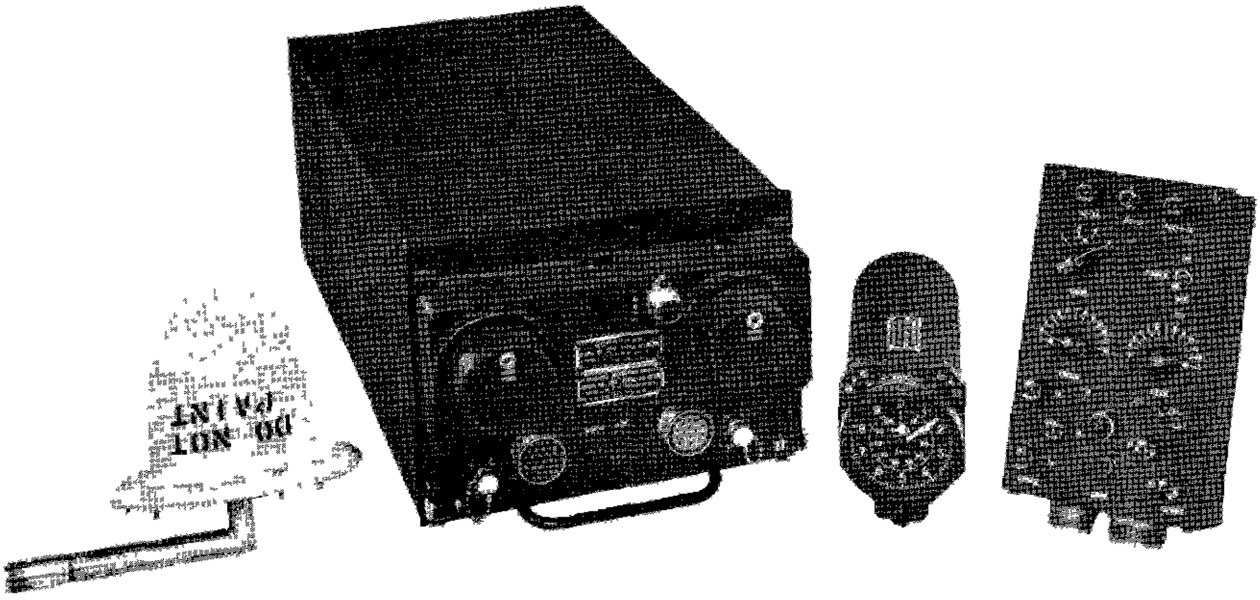


Fig 6 Hazeltine Interrogator

channel The search of the interrogator is automatically initiated and, when necessary, repeated The search time is approximately 14 seconds The two-pointer indicator precludes the necessity for a range-switch, and the multi-channel character of the equipment permits the elimination of the release switch employed on the earlier model DME

The Hazeltine interrogator, including all accessories except interconnecting cables, weighs 55 1/2 lb. and measures 23 1/4 by 10 1/2 by 7 1/4 in

The Hazeltine system, by virtue of the 9.5 Mc separation between radio frequencies, may be operated satisfactorily without resorting to high stability transmitters and receivers. In order that receivers properly accommodate transmitters having rather wide stability ranges, as well as compensate for frequency drift of the receiver local oscillator, they must have a broad-band characteristic The bandwidth of the receivers in the interrogators and the transpondors is approximately 5 Mc at 6 db down In order to provide steep skirts for the receiver response curve, a special circuit, known as a spike eliminator, is employed Adjacent and near-adjacent frequency pulses will result in a portion of their spectrum passing through the receiver Since the pulses will be received on a normally sloping skirt, the high frequency components of the adjacent frequency pulses will be amplified to a greater extent than the low frequency components The resultant pulse as it appears at the receiver output before spike elimination, will be distorted and will appear as a pulse of the proper width, but with pronounced spikes at the leading and trailing edges together with a relatively deep valley in the center By applying the receiver output pulses directly to one grid of a coincidence tube, and indirectly, after a delay of approximately one-third of the pulse width, to a second grid of the same coincidence tube, the spiked pulses are eliminated Fig 7 illustrates the action of the spike suppressor circuit It will be observed that the principle employed is the same as that employed by the decoder

The pulse-multiplex DME transpondor, a block diagram of which is shown in Fig 8, incorporates a crystal controlled transmitter and receiver This feature is not required for operation in conjunction with broad-band airborne receivers, but will operate satisfactorily with them The transpondor receiver, though possessing a closely controlled local oscillator frequency, is broadbanded in order to operate properly with low stability airborne transmitters The transpondor receiver is essentially the same as the interrogator receiver and is also followed by a spike suppressor A portion of the receiver output is used to operate an automatic gain stabilization circuit The gain is stabilized by maintaining a constant level of random noise Noise pulses from the receiver trigger a multivibrator at a rate determined by the noise level A diode counter feeds a bias voltage back to the if strip, which increases or decreases the receiver gain in order to maintain the pre-set noise level

The transpondor receiver also contains an echo suppression circuit, the purpose of which is to prevent multi-path (echo) pulses from combining with direct path pulses to form a proper code. Fig 9 illustrates how such echo pulses might lead to needless interrogation of a transpondor It may be pointed out that transpondor A of Fig 9, even though interrogated, will not reply with the proper frequency or spacing to be received by the aircraft receiver and decoder, however it has been needlessly interrogated, thus increasing its duty cycle and increasing the probability that some aircraft seeking replies from transpondor A will suffer increased count-down (ratio of replies to interrogations) In practically all cases, as shown in Fig 9, the echo pulses will arrive at the transpondor with appreciably less amplitude than the desired pulses The first pulse of a received pair causes the echo suppression circuit to reduce the gain of a video stage to a level determined by the amplitude of the first pulse Consequently, if the second pulse is small with respect to the first, it will not pass beyond this stage and will never reach the decoder

Incoming signals which successfully pass through the echo suppression and spike eliminator circuits are, after suitable amplification, applied to the input coil of the decoder Pulse pairs of the proper spacing result in a trigger pulse at the plate of the coincidence tube This pulse is used to trigger the dead-time multivibrator One purpose of the dead-time period is to prevent re-triggering of the transpondor by multipath pulse pairs following legitimate pulse pairs The need for this type of echo elimination should

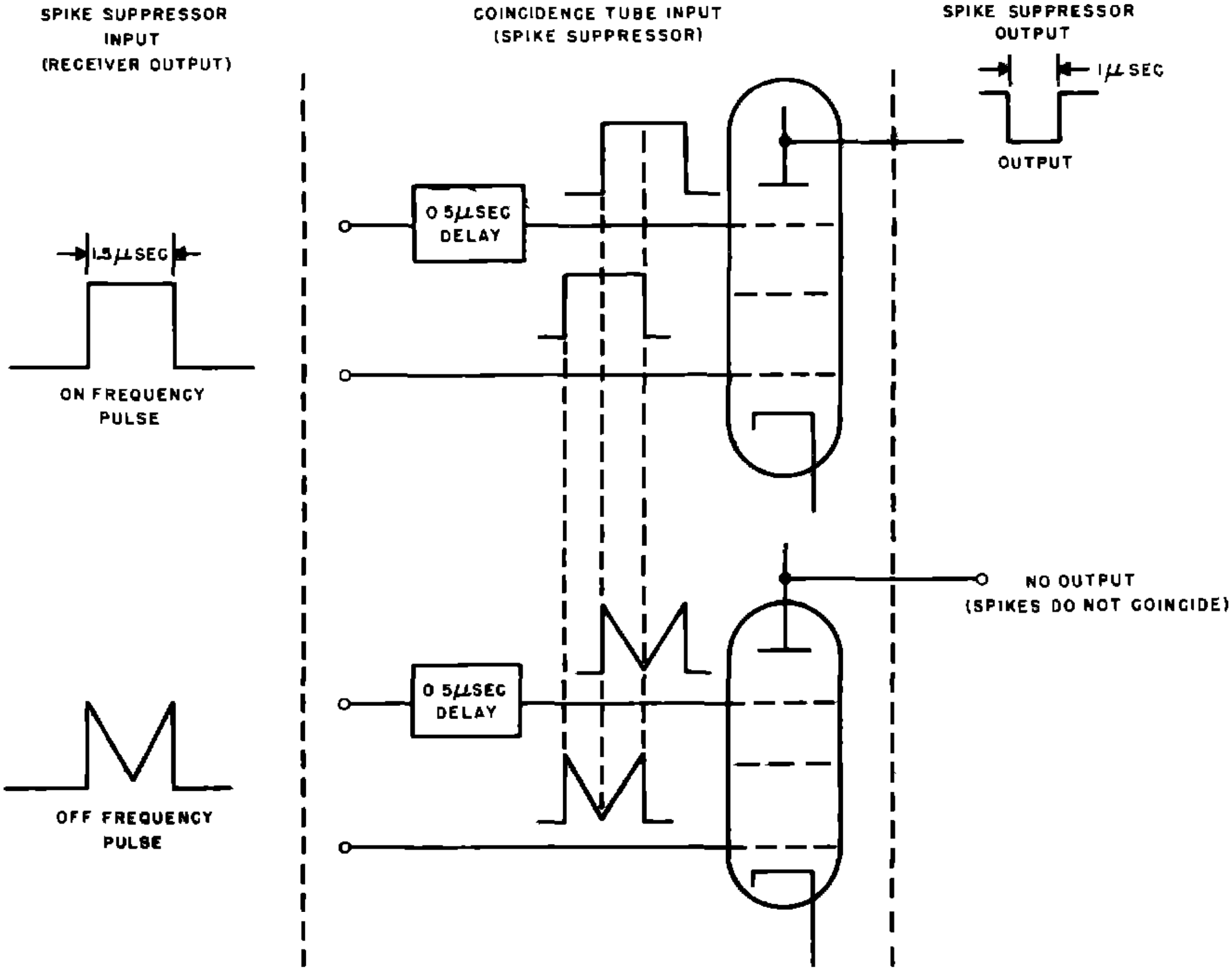


Fig 7 Spike Suppressor Action

not be confused with the need for the echo suppression circuit The echo suppression circuits previously discussed prevent the formation of a proper pulse code due to combinations of directly received, and delayed (multipath) pulse pairs Obviously, if the delay introduced by the multipath exceeds the pulse spacing, the direct path pulse pair will be followed by one or more multipath pairs, depending upon the particular site, all having the proper spacing Since there is no interlacing of the direct and reflected pulse pairs, the echo eliminator circuit will not be effective in such cases However, the dead-time multivibrator, by applying a cut-off pulse to a preceding amplifier prevents another trigger pulse from reaching the multivibrator until expiration of the dead-time The dead-time pulse serves two additional functions (1) to assist in preventing over-interrogation of the transpondor, and (2) to prevent pulses transmitted by the transpondor from retriggering it (ring-around) by pick-up at some point beyond the decoding process The output of the dead-time multivibrator, after wave shaping, is applied to the coder delay line. This line contains three coils, one excitation coil and two output coils The spacing between the two output coils is equal to the reply spacing of the transpondor The spacing between the input and second output coil is equal to 75 µsec, and is known as the artificial delay of the transpondor All transpondors within the system necessarily must employ the same artificial delay time, since all aircraft units are designed to subtract this time from

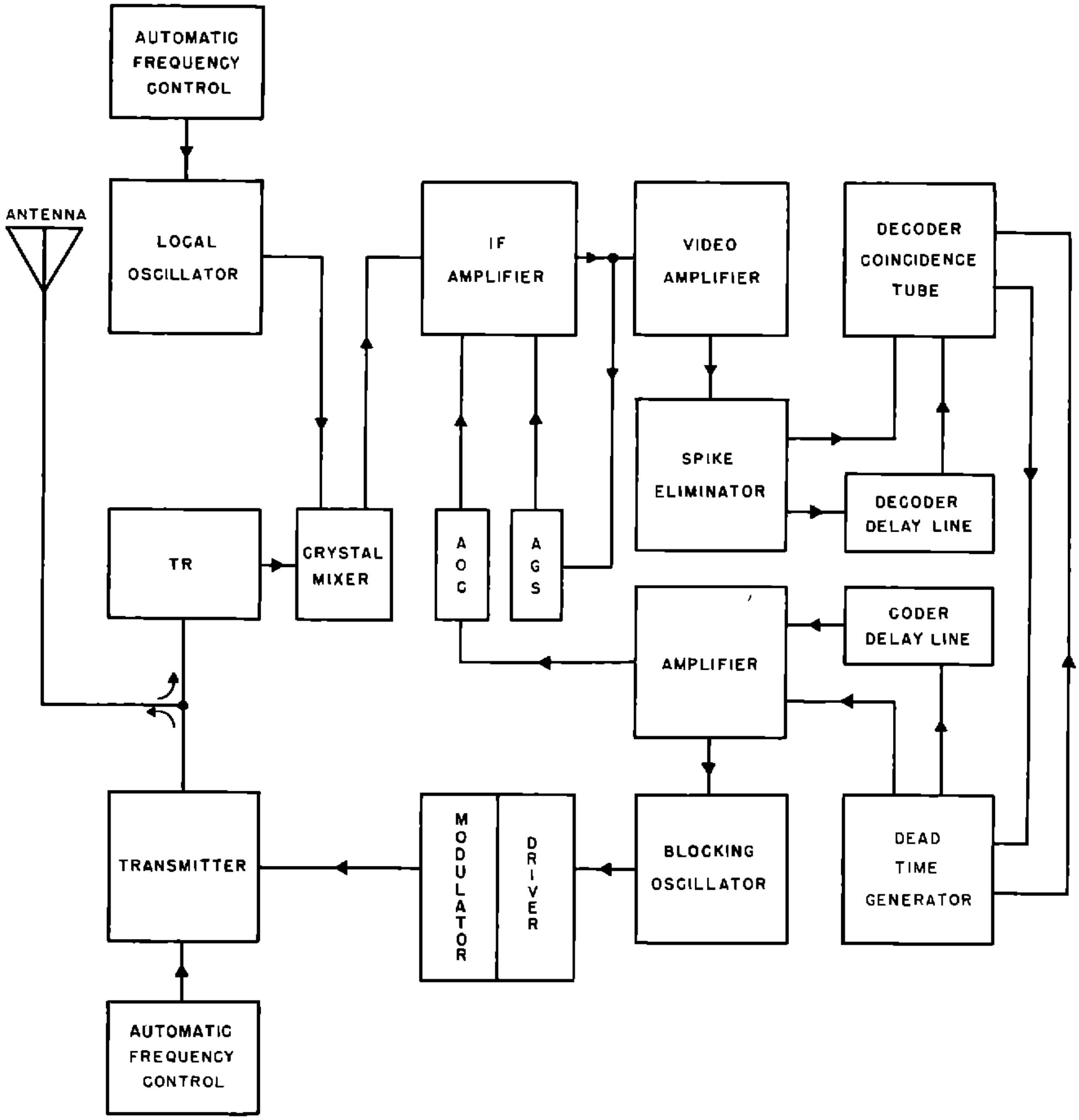


Fig 8 Hazeltine Transpondor, Block Diagram

that actually measured for the round trip pulse path from air to ground and return In a pulse multiplex system, the time measured by the interrogator is the time elapsed between transmission of the second interrogation pulse and the arrival of the second reply pulse at the interrogator This is necessary since neither decoder (transpondor or interrogator) recognizes that a proper signal has been received until coincidence is established The coincidence pulse, see Fig 5, always occurs at the time of the second pulse of a pulse pair

The two output pulses from the delay line are of the order of one volt in amplitude (due to high delay line insertion loss), and following necessary amplification are used to trigger a blocking oscillator, the output of

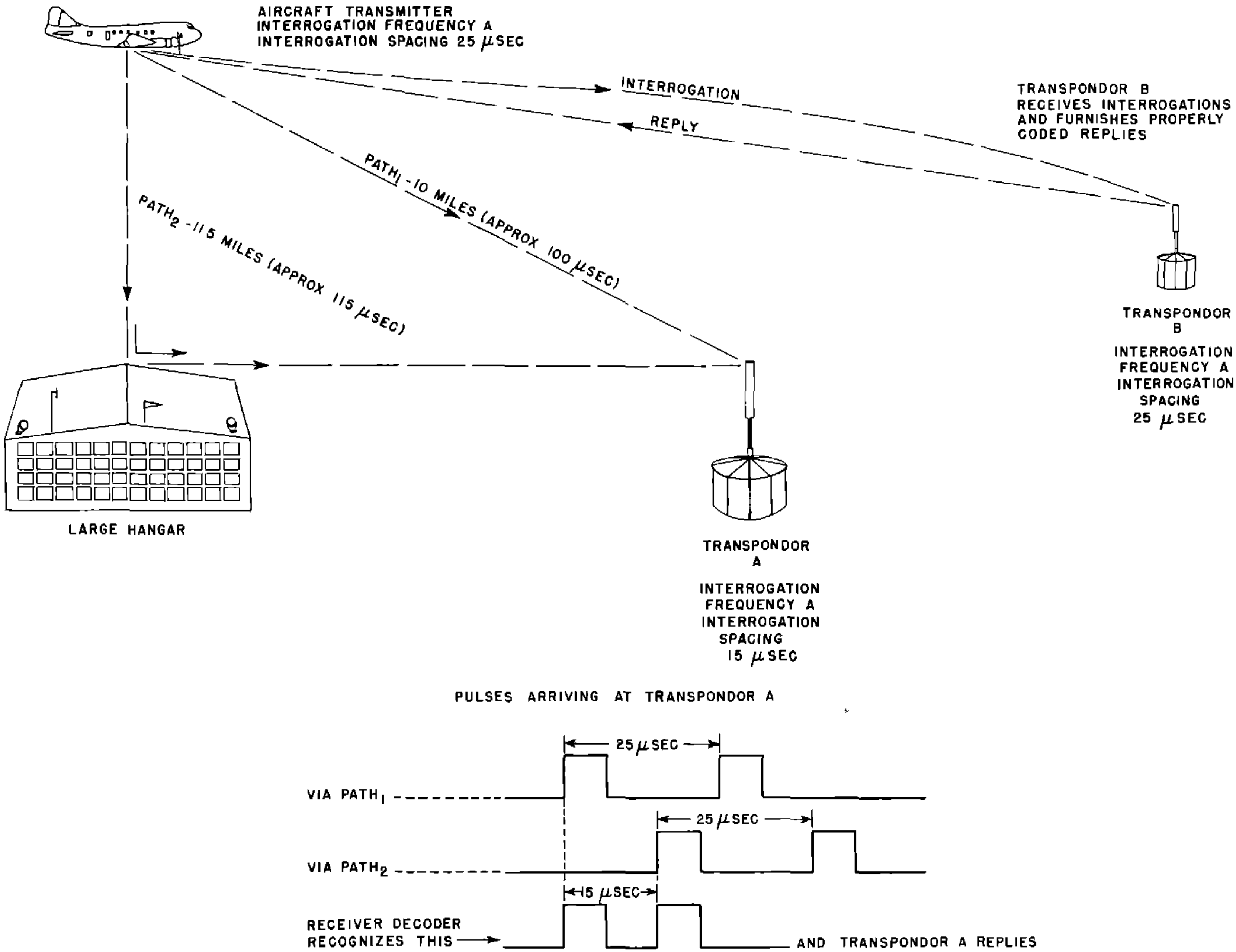


Fig 9 Needless Interrogation of Wrong Transpondor

which is fed to a 3E29 driver tube The modulator proper consists of three 3E29 tubes in parallel The use of hard-tube modulators of this type, having a rapid recovery time characteristic, makes it possible to employ the same modulator for both pulses of the pulse pair, as opposed to the two modulators employed in the aircraft transmitter

The rf oscillator is a Type 3C37 cavity controlled lighthouse tube. The peak power output of the transmitter is approximately 5 kw As previously pointed out, both the local oscillator and the transmitter frequencies are crystal controlled to a stability of about ±200 kc for the transmitter, and ±50 kc for the local oscillator The crystal control is exercised through means of an afc system and is not direct. The output of a crystal multiplier chain is compared with the frequency to be controlled, and a standard beat frequency is maintained between them A frequency discriminator controls the operation of a mechanical cavity-tuning arrangement in accordance with the beat frequency which is applied to the discriminator The antenna employed is a 4λ vertically stacked array, matched to a 50-ohm line. This antenna is shown in Fig 10 Fig 11 is a view of the Hazeltine transpondor

NARROW-BAND DME

The 51-channel DME built by Federal Telecommunication Laboratories is commonly referred to as a narrow-band, high stability type as compared with the Hazeltine version which employs wide-band receivers, and relatively low frequency stabilities in the interrogator The high stability characteristics of the Federal system permit close spacing of the rf channels employed The spacing between channels is 2 4 Mc, with 51 interrogation frequencies located in the lower half, and 51 reply frequencies located in the upper half of the 960 - 1,215 Mc band Since no individual frequency appears in more than one channel, double pulse transmissions are not required for channel discrimination, and consequently the system employs single-pulse transmissions throughout

The distance measuring principles of this equipment are identical with those of the pulse multiplex equipment and with the earlier types of DME The chief differences between the Hazeltine and Federal equipments are the following

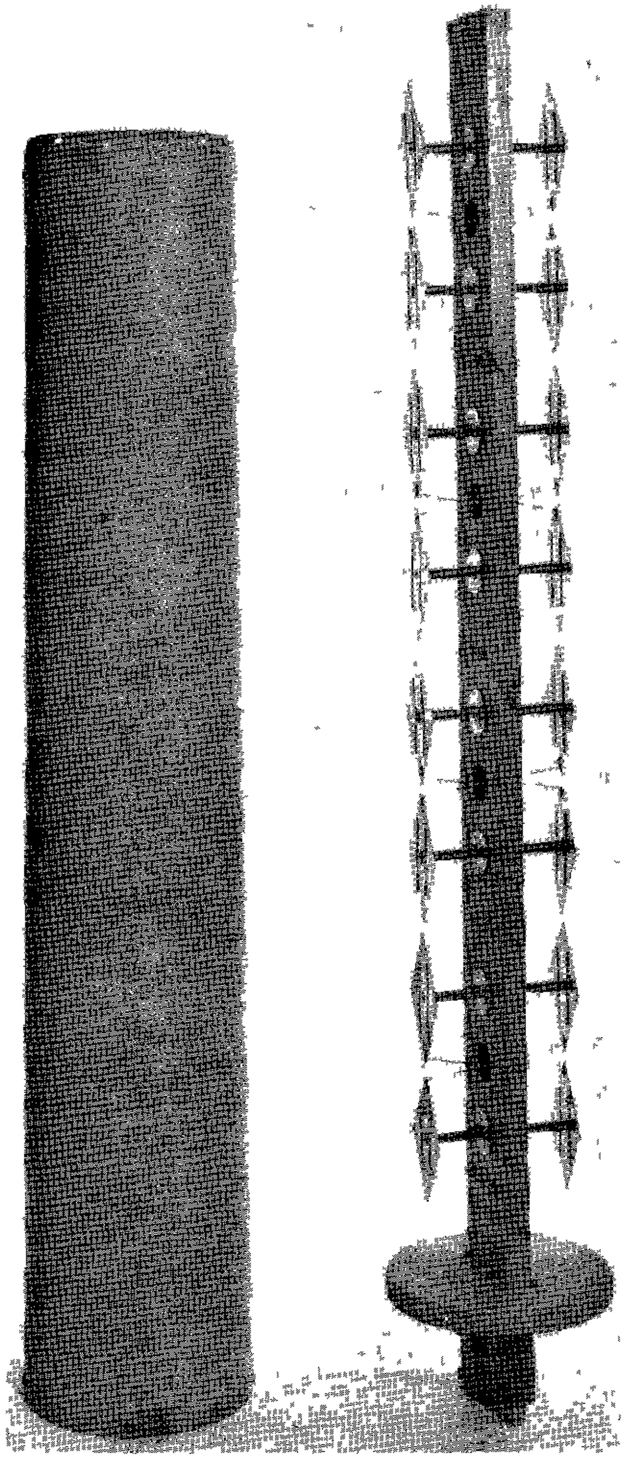


Fig 10 Hazeltine Transpondor Antenna

1 Automatic frequency control of the transmitter and local oscillator in the narrow-band system
2 Method of measuring the time interval equivalent to distance

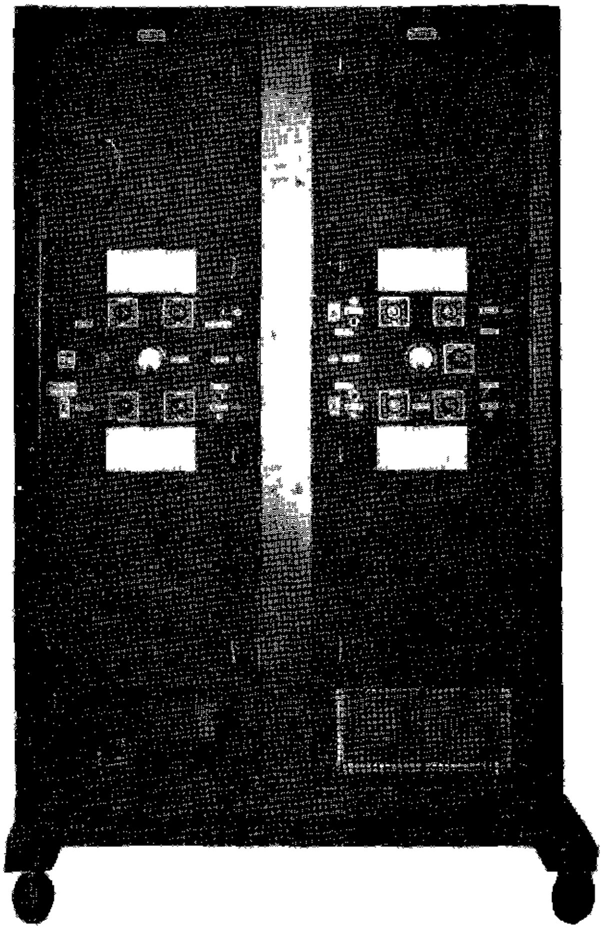


Fig 11 Hazeltine Transpondor

The aircraft interrogator, Fig 12, contains a total of 51 different frequency determining crystals, mounted about the periphery of a rotatable turret, shown in Fig 13 The frequencies of these crystals range from 42 to 47 Mc The position of the crystal turret determines which one of the 51 crystals will be operative on a particular channel The output of a crystal multiplying chain is used as the local oscillator signal for reception, and produces a 63 5 Mc if when mixed with an incoming signal of the proper frequency The energy from the crystal multiplier output also is mixed with a portion of the transmitter output to produce a beat frequency of 62 Mc when the transmitter is exactly on frequency After amplification through a broadband afc if amplifier the beat signal is applied to a frequency discriminator with a 62 0 Mc crossover point. The output of the discriminator controls the direction of rotation of a motor which positions the tuning plunger in the transmitter cavity in the proper direction to compensate for transmitter frequency shift Thus, it may be seen that control of the local oscillator is by conventional direct crystal control but, the stability of the transmitter oscillator is accomplished by comparison with a standard frequency and correction through means of afc The non-availability of a suitable power amplifier at the frequencies employed has thus far prevented the use of direct crystal control for DME transmitters. Since a single crystal per channel is employed as a reference standard for both the local oscillator and the transmitter afc, it is obvious that a constant difference must exist between the interrogation

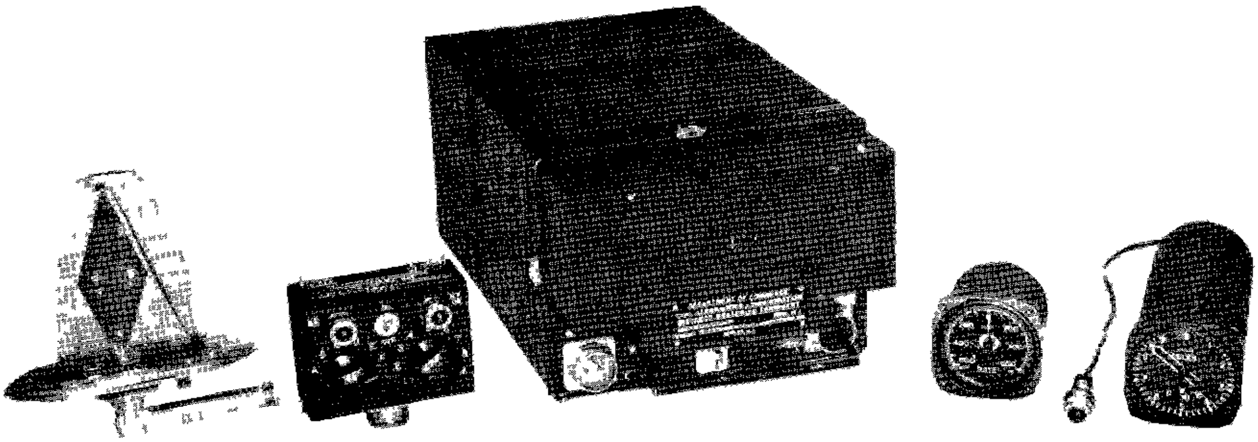


Fig 12 Federal Interrogator

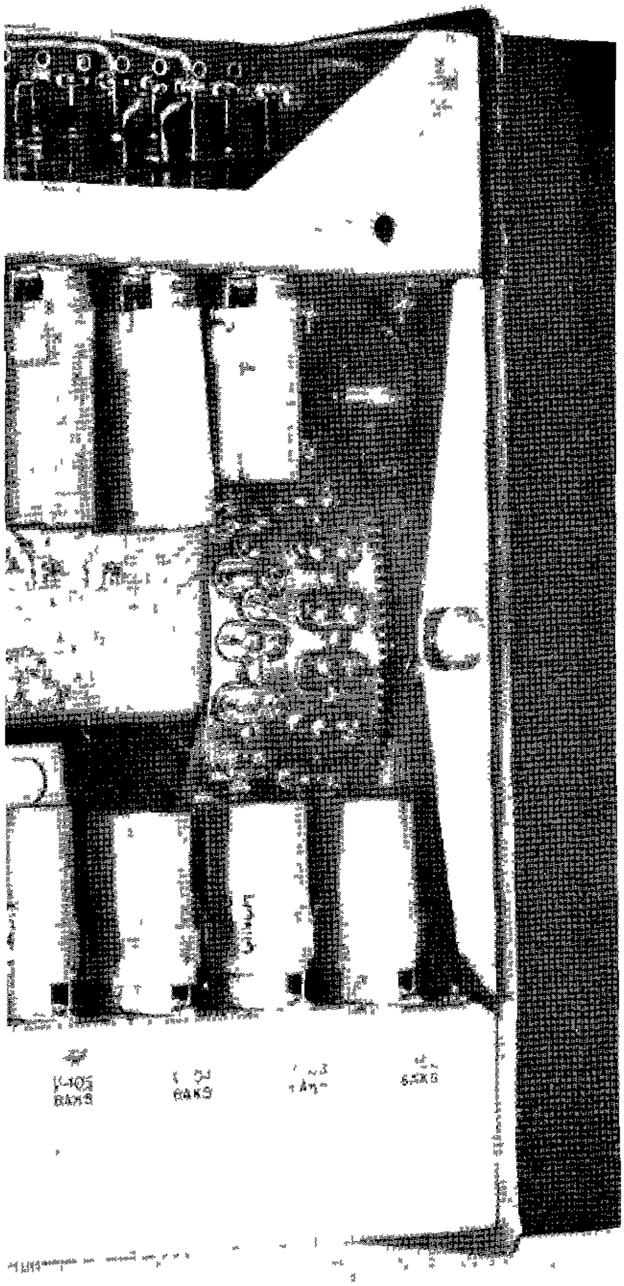


Fig. 13 Crystal Turret

and reply frequencies on each channel This difference is 125 5 Mc, and is the sum of the afc intermediate frequency and the receiver intermediate frequency

The output of the receiver converter is applied to the input of the 63 5 Mc if amplifier This amplifier is stagger-tuned to provide a 5 Mc bandpass At the output of the if amplifier, a special double discriminator is employed to eliminate adjacent-channel interference. This discriminator operates in such a manner that pulse spectra which are symmetrical with the if bandpass appear at the discriminator output as positive pulses Spectra which are asymmetrical with respect to the if bandpass appear as negative pulses Negative pulses are rejected by succeeding video circuits This circuit is commonly referred to as the McKinley discriminator From the above description, it is obvious that rf pulses in the adjacent channel, even though they may be considerably greater in amplitude than pulses at the desired frequency, will not pass into the video circuits of the receiver The order of rejection to adjacent channel pulses is about 100 db One disadvantage of this circuit, though not a serious one for DME purposes, is that reception of strong adjacent channel signals prevents the simultaneous reception of proper-frequency signals In other words, the utility of the circuit depends on a difference in time relationship, or the time of arrival, of wanted and unwanted pulses For this reason the circuit would not be effective for adjacent channel rejection in the case of cw signals In terms of the effective receiver bandwidths, the McKinley circuit provides exceedingly steep skirts, with maximum rejection at the adjacent channel frequencies.

The Federal airborne receiver incorporates an automatic gain control circuit, operating on the strength of the received signal. Conventional agc of this type is not usable in a pulse multiplex system due to the fact that more than one channel is transmitted on a single frequency In many cases the desired channel may be many decibels below some undesired channel on the same frequency, radio-frequency-wise Where agc is required in such a system, it is possible to operate on the signal after it has been found and is being tracked This is known as "gated" or "strobed" agc

In order to determine and continuously indicate the distance (the purpose of search and tracking), the narrow-band interrogator also employs a pair of gates In this system they are generally referred to as the "early" and "late" gates rather than the "narrow" and "wide" gates as in the pulse multiplex system The method of range measurement and indication is illustrated by a block diagram, Fig 14 V-212 is a 9 315 kc resistance stabilized oscillator which controls all functions The sine wave output of this oscillator is applied to the thyratron V-213, which produces positive trigger pulses at its cathode each time the applied sine wave at its grid goes positive These trigger pulses are applied to the control grid of a second thyratron V-214 This tube is effectively a coincidence tube in that it will not fire unless positive signals are simultaneously applied to its control and shield grids Periodic excitation to the shield grid is furnished by the master multivibrator V-215 The period of oscillation of this multivibrator is 30 cps during tracking and 150 cps during searching The positive pulse, or gate, delivered to the thyratron shield grid by the multivibrator must have a duration exceeding the period between two trigger pulses to insure coincidence with at least one of them Thus, sometime during the period that each positive pulse from the multivibrator is applied to the shield grid, a trigger pulse from V-213 will appear at the control grid of V-214 Should coincidence occur twice, the thyratron recovery time does not allow a second output pulse During the resultant interval of coincidence, a positive pulse appears at the cathode of V-214. This pulse is employed to trigger the modulator and also the Phantastron employed in the range-measuring circuits The advantage of this seemingly roundabout method of firing the transmitter will become apparent as the method of range determination is discussed Use of this multivibrator for selecting the 30 or 150 trigger pulses per second from the total of 9,315 per second, minimizes the possibility that any of the various aircraft operating within the system will synchronously interrogate with respect to each other Such a condition could result in one aircraft suffering severe count-down as a result of its interrogations arriving for extended periods of time, during the transpondor dead-time initiated by a second aircraft Precise synchronization of the interrogations of two or more aircraft can also result in ranging errors as a result of one aircraft repeatedly receiving replies initiated by some other interrogator Since no particular effort is made to accurately control the multivibrator repetition rate, all aircraft effectively interrogate at random with respect to each other

The 9 315 kc sine wave from the oscillator is also introduced to a two-phase precision goniometer Exact phase splitting is achieved by means of a condenser and resistor in series with one winding As the rotor of the goniometer is turned, the phase of the induced voltage varies linearly, by virtue of which linearity a high degree of range and rate accuracy may be obtained The induced sine wave is amplified by V-218B and used to fire thyratron V-219 Obviously the output pulses from V-219 will be delayed with respect to those from V-213 by the amount of phase shift introduced by the goniometer The output trigger pulses from V-219, hereafter referred to as range pulses, are applied to the control grid of coincidence thyratron V-220

The undelayed trigger pulse which fires the modulator is also applied to Phantastron V-216 and initiates a linear voltage decay at the plate of this tube This decay continues until the voltage at the plate equals a direct voltage applied, through control diode V-217B, from a potentiometer geared to the goniometer The gear ratio employed is 12 1, the potentiometer rotating once for every 12 rotations of the goniometer When the plate voltage of the Phantastron equals the control voltage from the potentiometer, a delayed trigger pulse, hereafter referred to as the selector pulse, is generated by the trigger amplifier V-218A, and applied to the shield grid of coincidence thyratron V-220 Since the delay of the range pulse and the delay of the selector pulse are both controlled by rotation of the goniometer shaft, the selector pulse is capable of tracking a range pulse from zero to maximum range

It is apparent that the range accuracy of the system is dependent on the highly stable sine wave oscillator rather than on the linearity of the Phantastron circuit and the shaft-driven potentiometer These latter two components serve only to select the proper range pulse, whereas the range pulse itself determines the actual time of firing of the coincidence thyratron V-220. Reference to Fig. 15, which shows the various waveforms and time sequences involved in the ranging circuits, will illustrate this point The duration of the selector pulse is long with respect to the duration of the range pulse, but its duration is necessarily less than the period between range pulses

When coincidence is established in V-220, the tube produces an 8 μsec positive pulse (the early gate) which is applied to the

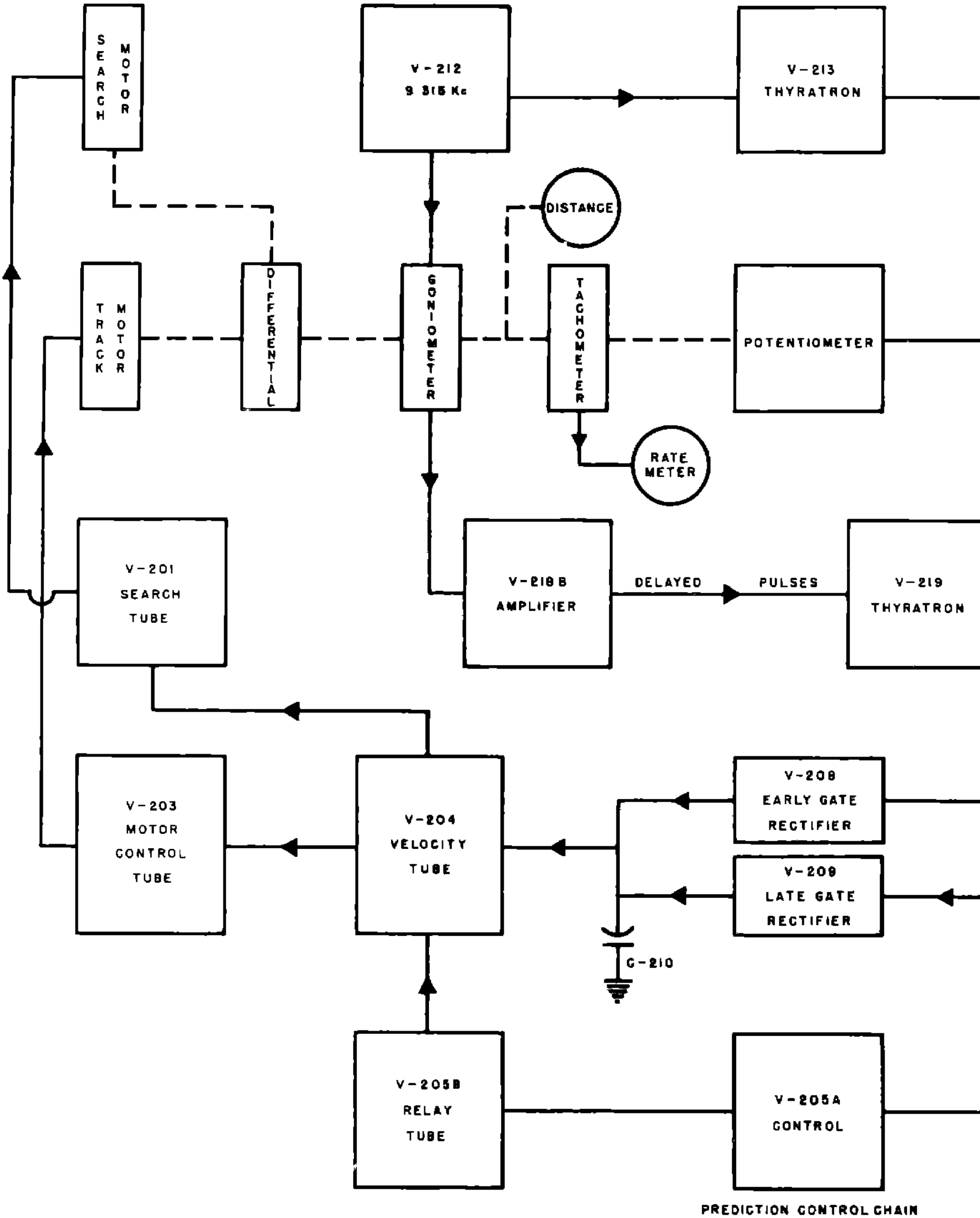
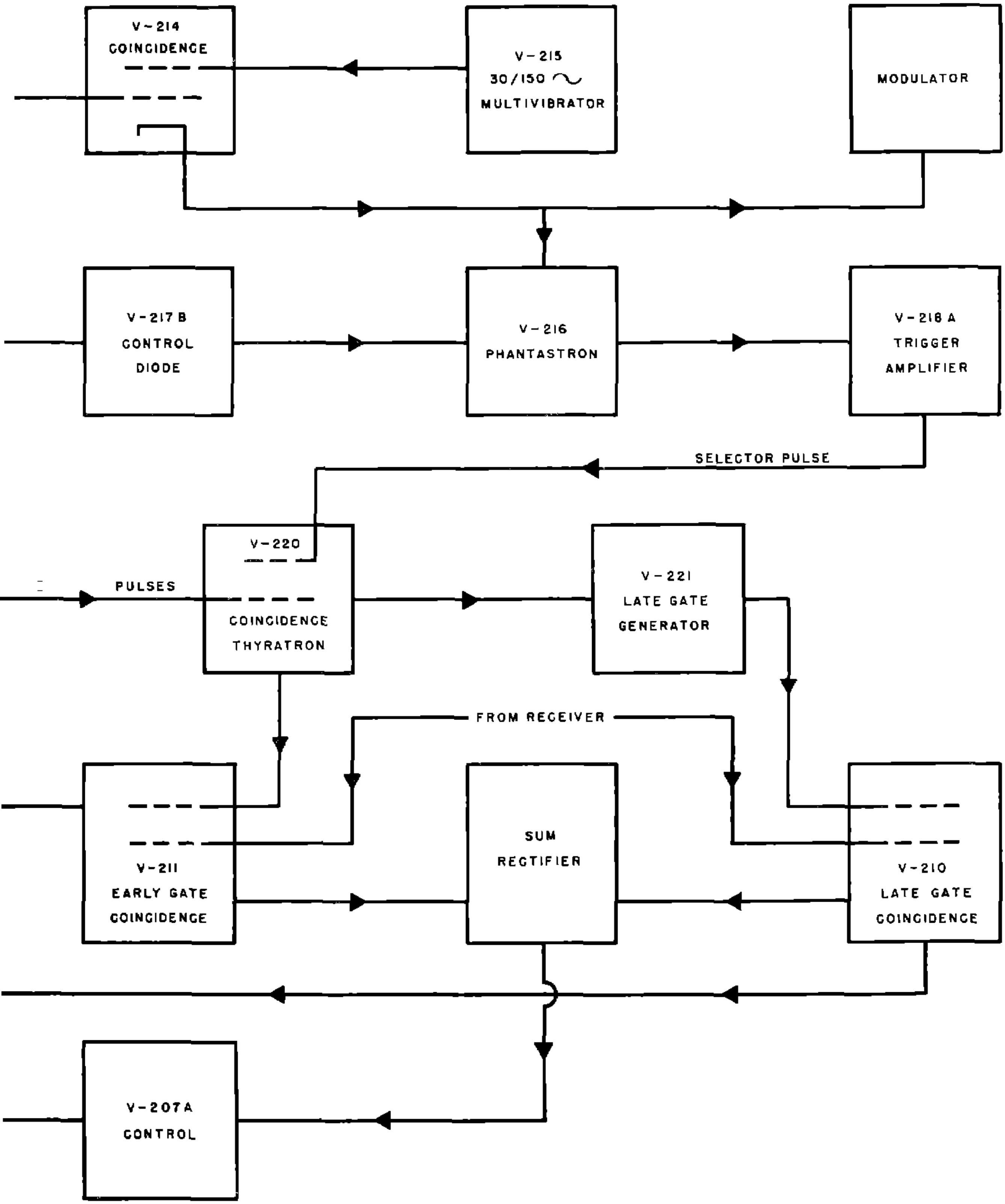


Fig 14 Block Diagram, F



Interrogator Ranging Circuits

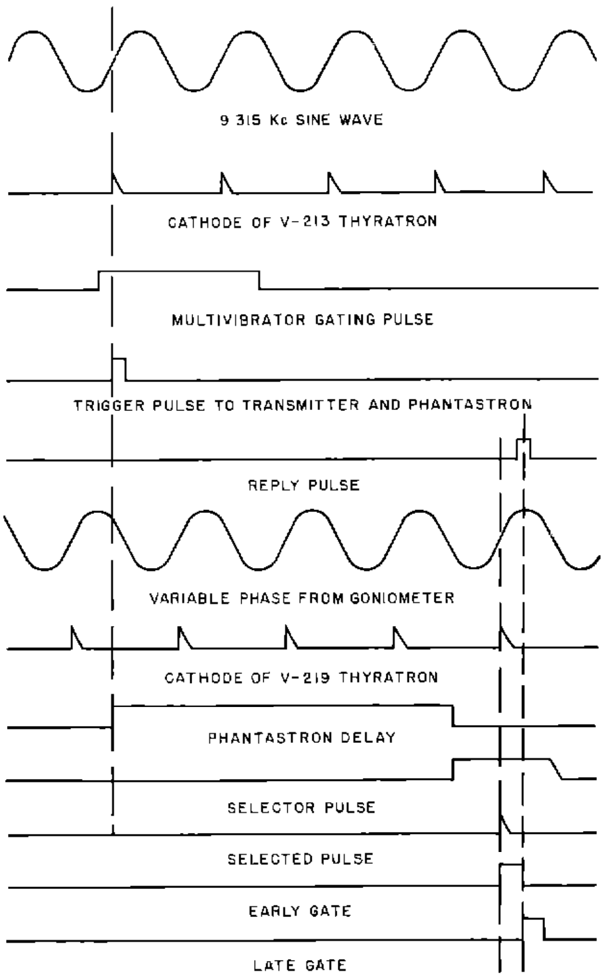


Fig 15 Range Circuit Timing Sequences Federal Interrogator

screen grid of V-211, the early gate coincidence tube, making that tube conductive in the additional presence of a reply signal from the receiver at its control grid The trailing edge of the early gate, with polarity inversion, is used to trigger V-221, the late gate generator, V-221 also delivers an 8 μsec pulse which is used to turn on V-210, the late gate coincidence tube The receiver output is also connected to the control grid of V-210 The outputs of these two tubes are differentially rectified through V-208 and V-209, the outputs of which are combined and integrated by C-210 The voltage on C-210 determines the plate voltage of V-204, the velocity tube, which operates the tracking motor through motor control tube V-203 The tracking motor in turn drives the goniometer The tracking motor is a special shunt motor designed to be operated below the breakdown point of its field current versus speed curve In this way, the field current required to control the speed is low enough to be supplied directly from the plate of a vacuum tube. Furthermore, the speed is roughly proportional to field current, so that the speed may be taken smoothly from one direction through zero to the other direction Reversal of rotation requires a reversal of field flux, which is achieved by means of an auxiliary field winding of constant flux which opposes the control field flux

Servo feed-back is provided by a permanent magnet tachometer geared to the goniometer shaft The tachometer output is amplified and supplies a negative feed-back signal for the primary servo-loop

The voltage output from the tachometer varies linearly with speed, and accordingly is an accurate measure of the rate of change of distance A zero-center dc voltmeter is employed to present this rate information to the pilot Because of the inherent jitter of the reply pulses in the tracking gates, chiefly due to propagation characteristics, a large amount of integration is required in the rate indicating system This integration is supplied by means of submerging the meter movement in a silicone fluid

The prediction control chain shown at the bottom of the block diagram of Fig 14 makes it possible for the indicator to continue to display distance and rate information when the reply signal is lost, up to a limit of approximately 3 sec During tracking, V-207A is cut-off by a negative signal from the sum rectifier Upon disappearance of the signal, this tube rapidly becomes conductive, which in turn causes V-205A to become conductive The conduction of V-205A cuts off relay tube V-205B, releasing its plate circuit relay. Release of this relay causes the plate potential of V-204 to be switched to the average value of the velocity voltage, which is provided by a memory condenser that has been charged to this potential during the preceding interval of tracking

There exists some question regarding the value of rate memory with respect to simple distance memory The assumption is made in the case of rate memory that the aircraft will continue on the same course and at the same rate during the memory, or prediction period In many cases, disappearance of the reply signal is due to banking of the aircraft, which is usually accompanied by a change in course and an accompanying change in rate

The operation of the ranging circuits has been described in terms of the tracking function. During search, the tracking motor is de-energized and a differentially connected search motor is energized by 28 volts dc through operation of a relay in the plate circuit of the search tube V-201 The search tube is nonconducting during tracking and the relay is de-energized When gated replies no longer appear at the gate rectifiers, the tracking tube is cut-off rapidly by a negative charge built up on C-210 as the result of a 3 μamp bleeder current which flows at all times During tracking, the gate rectifiers compensate for this current by slightly misaligning themselves about the gated signal When the tracking tube is cut-off, its high plate voltage applied to the grid of the search tube, causes the latter to conduct The speed of the search motor is such that a distance of 115 statute miles may be searched in 7 seconds The pilot's indicator is, of course, driven by the same gear train which drives the goniometer during both search and tracking.

During the search period, the repetition rate of the transmitter is increased to 150 pps This increase in pulse rate increases the ratio of wanted to unwanted replies (replies to other aircraft), and thus permits the faster search time

The Federal transpondor is shown in Fig 16 This unit, like the interrogator, employs crystal control throughout Since the necessity for conservation of space and weight is not as stringent in the case of ground equipment, separate crystals are used for controlling the transmitter afc and the local oscillator of the receiver The crystals employed in the transmitter afc have a natural frequency of the order of 20 Mc After frequency multiplication, the third harmonic of the crystal-controlled output is heterodyned against a portion of the transmitted rf energy The resultant beat frequency is 30 Mc, with the crystal-generated frequency being the lower of the heterodyned frequencies After three stages of amplification by a 30 Mc if amplifier, the beat signal is applied to a frequency discriminator The resonant circuits of this discriminator consist of two brass coaxial lines, each of which is tuned at its open end by a combination of fixed capacitors and a trimmer capacitor If the beat frequency is above 30 Mc, the discriminator produces a positive pulse output, if below 30 Mc, it produces a negative pulse output After amplification, this pulse is applied to a phase splitter, the output of which fires one of two thyratrons The phase splitter is a triode, the output of which is applied to one thyratron and the cathode output of which is applied to the second thyratron Since the polarity of the signals will be opposite, only one thyratron will fire for a discriminator output pulse of a given polarity Neither tube will fire when the transmitter is operating at its assigned

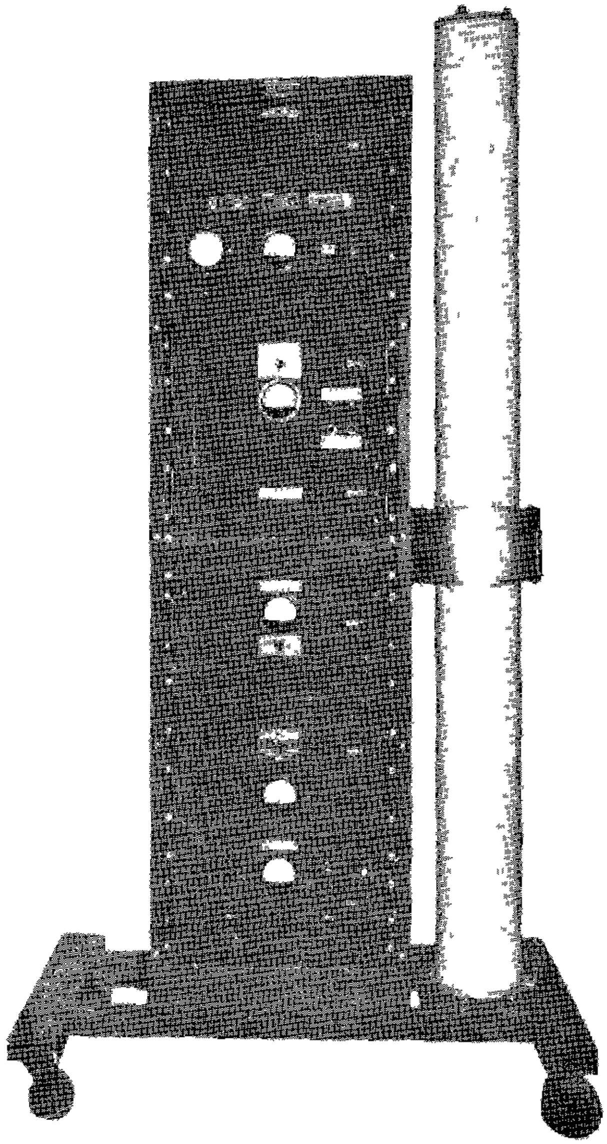


Fig 16 Federal Transpondor and Antenna

frequency Firing of either thyratron completes a circuit to the transmitter tuning motor which causes it to rotate in the proper direction to correct the frequency shift

The transpondor receiver differs from the airborne receiver in that a 30 Mc if amplified is employed in the former The transpondor receiver is followed by a McKinley discriminator for rejection of adjacent channel interrogations

In order to obtain the artificial delay required in a DME system, a Phantastron circuit is used The delay inserted is approximately 40 u sec Less artificial delay is required in single pulse systems than in pulse multiplex systems since the spacing between the two reply pulses must necessarily form a portion of the delay

In order to provide a relatively high duty cycle rf signal for airborne receiver agc purposes, and to maintain a constant transmitter output duty cycle at all times, the transpondor fires continuously at the rate which would be demanded by 50 interrogating aircraft This constant duty cycle mode of operation is helpful in stabilization of the transmitter afc, permits use of signal bias circuits and has a number of lesser advantages This feature is achieved by operating the receiver, in the absence of interrogations, at a sufficiently high gain level to cause random noise pulses to trigger the transmitter at a rate of approximately 1,500 pps As interrogations are received, the receiver gain is automatically reduced to the point where the sum of the interrogation pulses and the random noise pulses is equal to 1, 500 per second In other words, the greater the number of legitimate replies to aircraft interrogations, the less the number of internally generated random replies A balance of receiver gain about the level required is accomplished by integrating the reply trigger pulses, and, when the integrated voltage exceeds a certain value, corresponding to an excess of 1, 500 replies, reducing the receiver gain through a dc amplifier

Identification coding, as provided by the Federal transpondor, exhibits itself in the aircraft as gap coding, however, the ground transmitter is never actually turned off Instead, the receiver local oscillator is disabled, during which time no synchronized replies are returned to interrogating aircraft

The antenna, presently being furnished with the Federal transpondor, is a stacked array of nine discones Each discone has an almost unlimited bandwidth above 900 Mc, but the combination has a low standing wave ratio only throughout the 960 - 1,215 Mc band This antenna is shown in Fig 16

TESTS

RANGE ACCURACY

The distance indicating accuracy of a pulse-type distance measuring system is dependent upon the following factors

1 Accuracy of the appropriate time interval measurement, and conversion of this measurement into an indication of distance
2 Accuracy of the artificial delay introduced by the transpondor
3 Propagation
4 Accuracy to which the indication may be read in the aircraft
5 Altitude of the aircraft

By far the most important of these is item 1 Fig 17 is an error curve characteristic of the Hazeltine type airborne interrogator and Fig 18 is a similar curve for the Federal equipment These curves include only those errors introduced by the airborne unit The specification to which these equipments were built contained an accuracy requirement of plus or minus three per cent or plus or minus one-half mile, whichever is the greater Inspection of the curves reveals that the Federal interrogator is well within these limits, thus allowing for more than adequate tolerance in the other accuracy determining factors The error curve for the Hazeltine equipment, Fig 17, indicates that essentially zero tolerance is available for other error sources It should be pointed out that the accuracy of distance measurement is not significantly related to a particular type of system, i e, narrow-band or pulse-multiplex Examination of the circuits employed in the Hazeltine equipment for distance measurement and indication reveals that the electronically created range voltage the dc voltage proportional to distance is extremely linear (well within one per cent) and, that the major portion of the errors shown in the curve of Fig 17 are introduced by the servo-system which drives the indicator It is reasonable

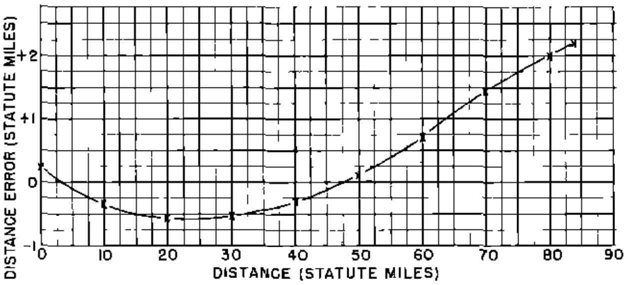


Fig 17 Error Curve, Hazeltine DME Interrogator

are of sufficient size so that they can be read accurately to 0 1 mile (by interpolation in the case of the Federal equipment) at a normal pilot-to-indicator separation There is little to be gained by calibration at smaller intervals, as 0 2 mile appears to be adequate and the present state of the art does not permit more accurate measurement of the time interval

It should be remembered that the distance measured by DME is the straight-line, or slope line distance, and not the horizontal distance Thus, an aircraft flying at 10,000

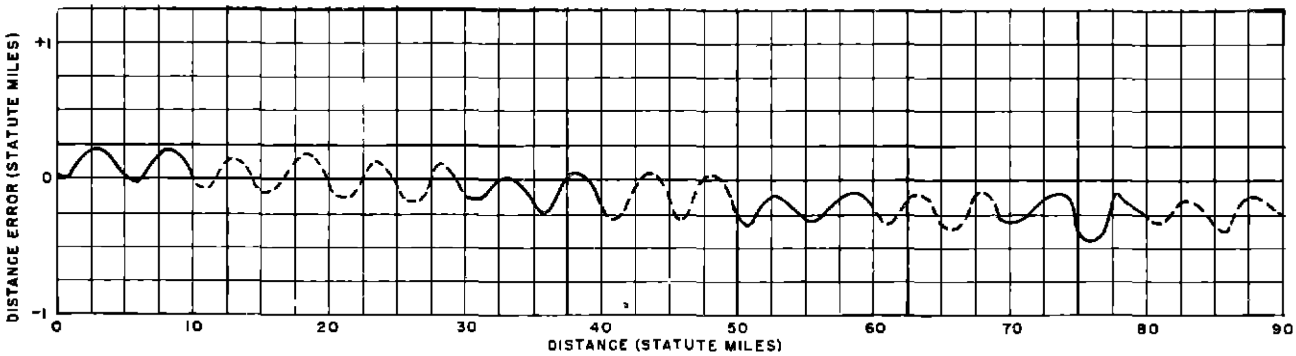


Fig 18 Error Curve, Federal DME Interrogator

that follow-up circuits can be made to faithfully reproduce the linearity of the range voltage

With respect to the accuracy of the artificial delay, indications are that the Hazeltine method of providing this delay by means of a magnetostriction line is probably preferable The magnetostriction line is a passive device and varies insignificantly with the temperature and voltage variations encountered at the ground station Accuracy of the Phantastron delay provided by the Federal transpondor is dependent upon the stability of a number of circuit components In actual operation, the stability of the Phantastron delay is of sufficient order to provide the desired over-all distance measuring accuracy

Errors due to propagation, causing "jitter" of the reply pulses in the distance measuring gates, is of the order of 100 feet and may be ignored

The Federal interrogator is provided with an indicator on which the smallest distance calibration is 0 2 mile, whereas the smallest calibrated increment on the Hazeltine equipment is 0 1 mile Both instruments

feet directly above the transpondor would indicate approximately two-miles distance. This error becomes increasingly small as the aircraft flies further from the station At a slope-line distance of five miles, the horizontal distance is 4 6 miles Fig 19 is a graph showing the relation between slant and horizontal distance for various altitudes

RANGE CAPABILITY

The range capability of a distance measuring system is dependent upon a number of factors, chief among which are

1 Transmitter Power
2 Receiver Sensitivity
3 Antenna Gain
4 Antenna radiation pattern (aircraft and ground)
5 Aircraft attitude

On the basis of theoretical evaluation alone, it may be shown that the free-space range of a distance measuring system having the characteristics of present equipment, is of the order of 600 miles This statement assumes proper adjustment and operation of the system and ignores two very important factors

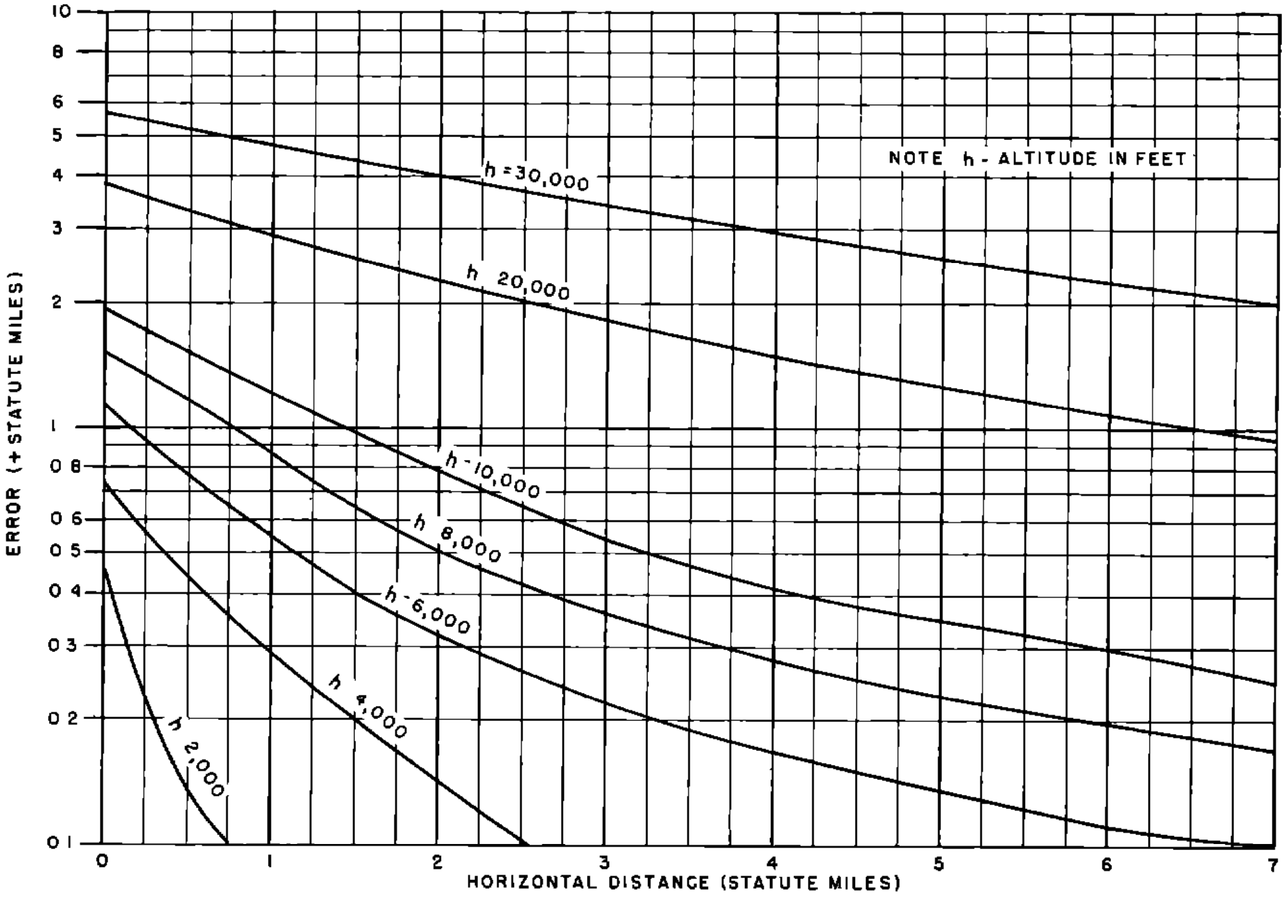


Fig 19 Slant Distance Error

1 Antenna pattern nulls due to the interference of direct and reflected energy, and
2 Shadowing of the aircraft antenna due to aircraft attitude

Quantitative data regarding the magnitude of range capability deterioration due to these factors is presently being obtained Fig 20 shows the actual antenna pattern obtained at a typical DME installation The data for this pattern were obtained with a constant aircraft attitude, and do not include fluctuations of signal strength due to aircraft climbing and banking A study of this pattern and extrapolation to 100 miles reveals that sufficient signal strength is available within the coverage range of 100 miles above line-of-sight to properly operate the system, even through the deepest nulls Preliminary investigation of signal fluctuations due to aircraft attitude indicates that the magnitude of these variations presents a far more serious problem than the presence of the ground nulls in the antenna pattern During a standard rate 360° turn (approximately 15° bank) the signal strength variation in microvolts at the receiver was 25 db

CODERS AND DECODERS

Fig 21 is an acceptance curve of a typical decoder employing a magnetostriction delay line This graph shows receiver sensitivity versus rf pulse spacing applied at the receiver terminals. Tests have shown that a variation of ±15 v. in line voltage results in the acceptance bandwidth of the decoder changing in the order of ±0 25 μsec

Temperature change of ±80° C from a mean of 20° C results in a change in the delay of the line of plus or minus two per cent

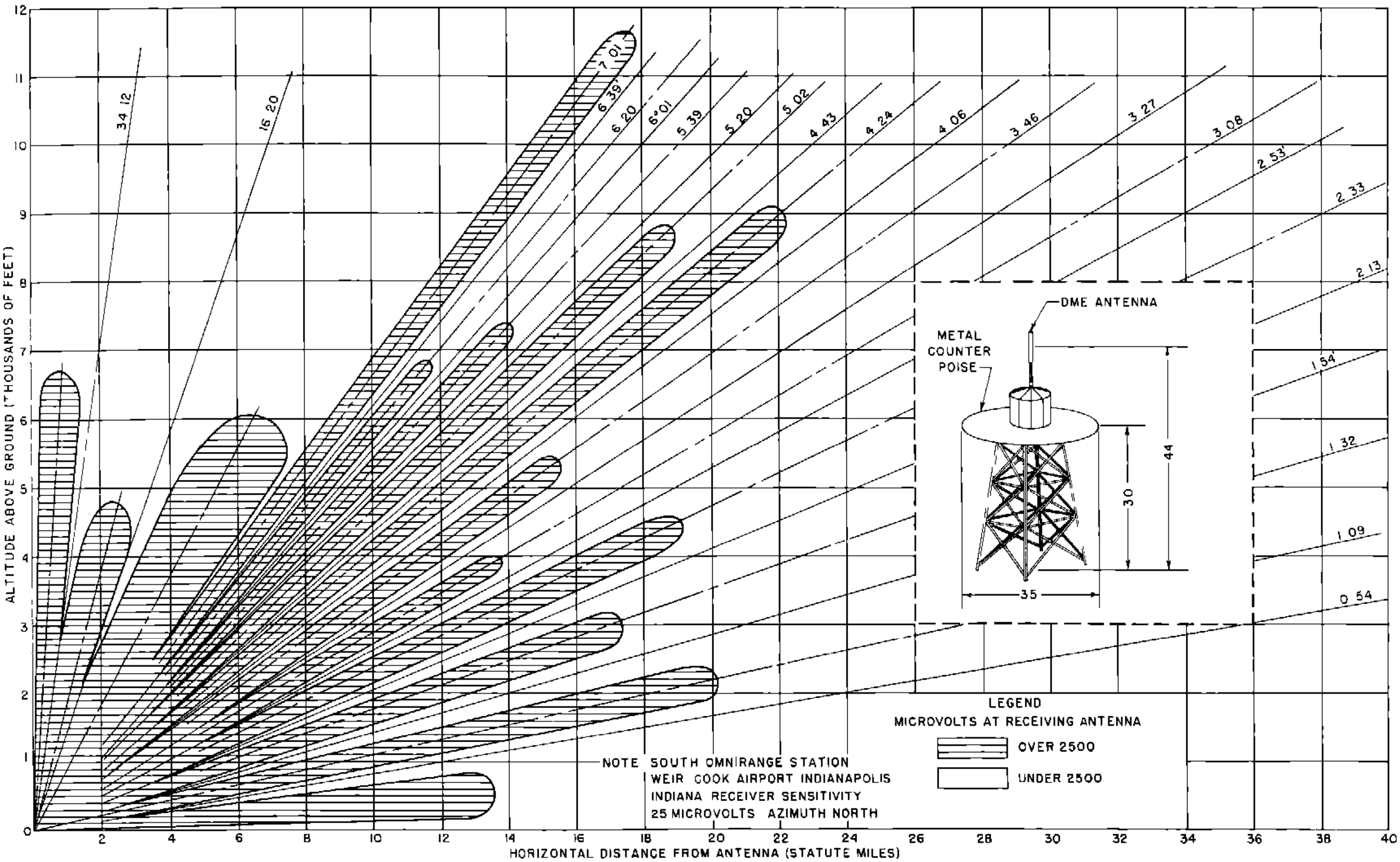


Fig 20 Transpondor Antenna Pattern, Hazeltine Four-Wavelength Antenna

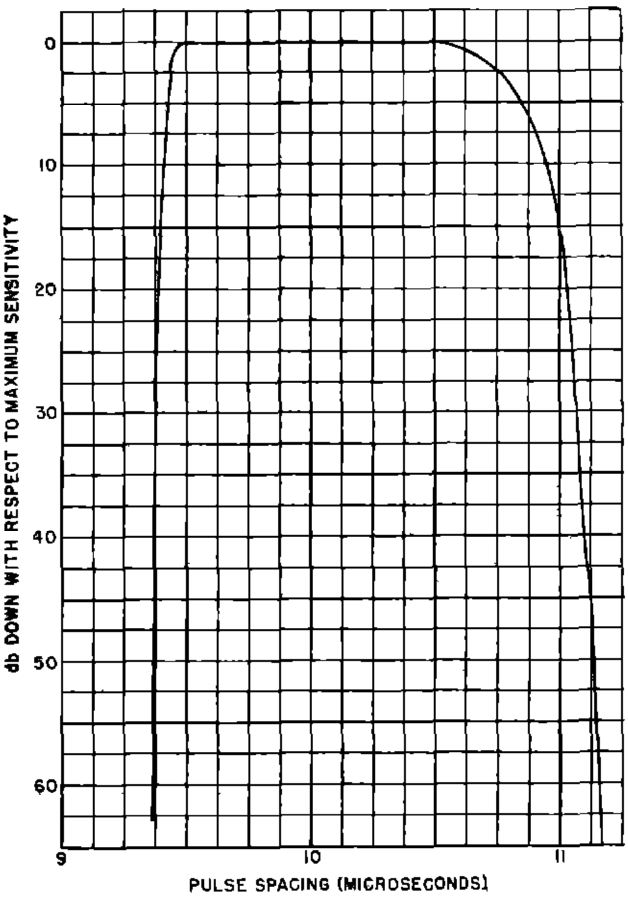


Fig 21 Decoder Performance Curve

This figure applies for both coders and decoders [7]

FREQUENCY STABILITY OF TRANSMITTERS

Experience has shown that frequency variation of a properly operating automatic frequency controlled DME transmitter (Federal ground and airborne and Hazeltine ground) is within ±200 kc This figure applies for variations in temperature, line voltage and repetition rate Failure to remain within this limit is usually due to improper operation of the afc system, which can, under some conditions of breakdown, actually pull the transmitter well off of the desired frequency Evidence of this happening has been sufficient to indicate that additional development is required along these lines Most of the trouble encountered thus far can be corrected by improved shielding of the discriminator circuits. Pick-up of the high-level modulator pulse by the discriminator output amplifiers often leads to a constant correction voltage being applied to the afc tuning motors. The polarity of this pulse is, of course, independent of the radio frequency A good bit of trouble also has been encountered due to change in afc sensitivity, as a result of sudden changes in repetition rate

FREQUENCY STABILITY OF RECEIVERS

Stability of the local oscillators, either directly controlled (Federal) or afc-controlled (Hazeltine), has been of the order of ±50 kc Practically no trouble has been experienced with these circuits

RECEIVER BANDWIDTHS

A receiver selectivity curve for the Federal type of receiver [8] is shown in Fig 22 Fig 23 is a selectivity curve for the Hazeltine receiver In the case of Fig 22, the selectivity curve includes the action of the McKinley discriminator. Fig. 23 represents the effective response curve of the Hazeltine equipment including action of the spike suppressor circuits The difference in bandwidths between the two curves is due to the fact that the Hazeltine receivers must be capable of proper operation under conditions of unstabilized local oscillator and transmitter drifts

IMAGE REJECTION

The image rejection on all receivers tested was between 50 and 65 db

LINE VOLTAGE VARIATION

The effects of line voltage variation on the various characteristics of a pulse multi-

[7] See Footnote 6

[8] Federal Telecommunication Laboratories T M No 330, "Performance Tests of Distance Measuring Equipment," August 1948

plex interrogator are shown in the following table

Line Volts	Power Output (db above 1 watt)	Receiver Sensitivity (db below 1 volt) Lock-in	Unlock	Transmitter Freq (Mc)	Receiver Freq (Mc)
90	31 4	*	82	1045 0	1149 6
95	33 4	*	83	1044 9	1149 8
100	34 5	*	84	1044.8	1150 8
105	35 7	84	85	1044 7	1151 4
110	36 5	84	85 5	1044 6	1151 5
115	36 5	86	87	1044 6	1151 5
120	36 5	86	87	1044 5	1151 7
125	36 5	84 5	86	1044 4	1152 0
130	36.5	83	84	1044 5	1152 0
134	36 5	81	82 5	1044 5	1152 1

*Indicator would not lock-in at any sensitivity

A study of the foregoing table discloses that a variation of line voltage between 105 and 125 v does not seriously affect normal operation of the interrogator Below 105 v. the interrogator becomes unusable due to inability to lock in

MEMORY

As previously explained, the purpose of DME memory is to permit the continuous indication of distance during relatively short periods of signal absence In the case of velocity memory, the distance continues to change at the same rate and in the same direction at which it was changing just prior to fading of the signal Since a large proportion of signal fades are a result of aircraft turns (thus changing rate), it is felt that simple distance memory is preferable to velocity memory. In this case the pilot's indicator continues to display the distance reading last recorded before the signal fade

It is possible to design the memory circuit so that it will continue to indicate this reading almost indefinitely Obviously, a practical limit must be chosen There are a number of factors which determine the most logical choice of memory duration In order that the memory be useful, it is essential that the reply signals still lie within the tracking gates when the signal again becomes available The memory time permissible to meet this condition depends upon the rate of movement of the aircraft with respect to the transpondor, and the duration of the tracking gates The curves in Fig 24 show the useful memory time versus aircraft rate of movement for several different gate widths

Assuming that the reply signal is centered in the tracking gates at the time of a signal fade, it is obvious that movement of the aircraft in excess of the distance equivalent of one-half the total gate width will cause the reply signal, when again received, to be out of the tracking gates When this happens, search must be reinitiated and the advantage gained by memory is no longer valid

During memory, the distance reading is in error by an amount determined by the instantaneous value of memory time elapsed, and the rate of movement of the aircraft Percentage-wise, this error is greater at the shorter distances At ten miles distance with a 20 μsec total gate duration, the error at the termination of memory could amount to ten per cent of the distance indicated. This percentage decreases with distance, and fortunately it is at the greater distances that signal fading is most likely to occur

On the basis of the experience previously outlined, it appears that memory will be needed most during course changes of the aircraft The standard aircraft turn is at the rate of 3° per second, or two minutes for a complete 360° turn In the latter case, only during about 90° of the turn, on the average, will the aircraft antenna (with an under-fuselage installation) be shielded to the extent that a signal fade is likely to occur This would be equivalent to approximately 30 seconds, the exact figure depending upon field intensity in the turning area, which is a function of the ground antenna pattern and aircraft distance It might seem desirable to extend the memory

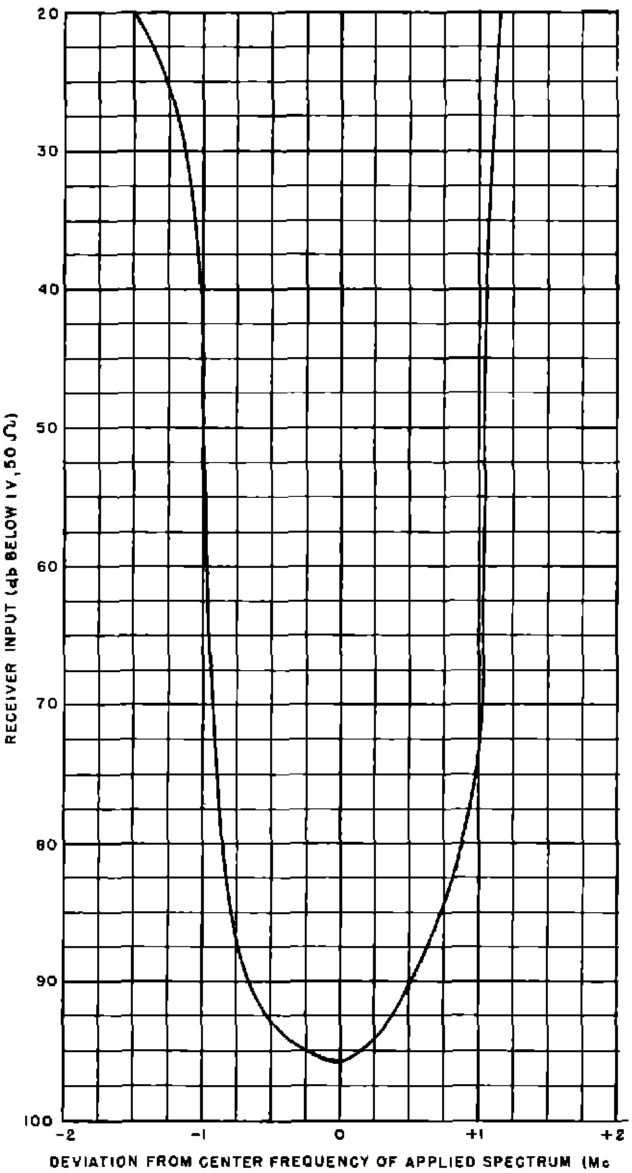


Fig 22 Selectivity Curve, Federal Receiver (interrogator)

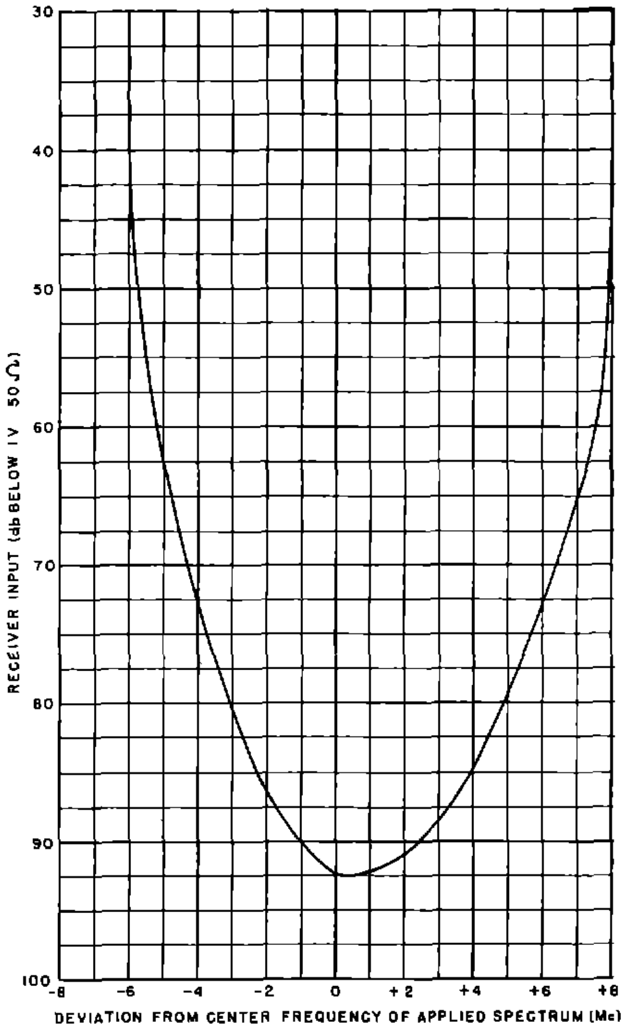


Fig 23 Selectivity Curve, Hazeltine Receiver (interrogator)

time to the order of 30 seconds, in view of the fact that during a turn the aircraft rate of movement is generally low, leading to negligible inaccuracy and also minimizing the chance of the reply signal moving beyond the locked gates If held operationally desirable, the memory could be thus extended, provided the aircraft is not operating within a highly saturated DME service area

In a highly saturated system, the maximum usable memory time is limited by still another factor In a pulse multiplex system, with a large number of aircraft operating DME equipment, the ratio of the replies intended for a particular airplane with respect to other replies on the same frequency, but intended for other aircraft, is small Consequently, the probability of unwanted replies being received in the tracking gates of an individual interrogator increases with traffic density When, as a result of reply path failure, an aircraft fails to receive its intended replies, it also will lose all other replies transmitted by its parent transpondor to other interrogating aircraft However, if the aircraft is within line-of-sight range of other transpondors, which are transmitting on the same reply frequency, even though the modes be different, a certain percentage of these random replies will interlace and pass the aircraft decoder Of those which successfully pass the decoder,

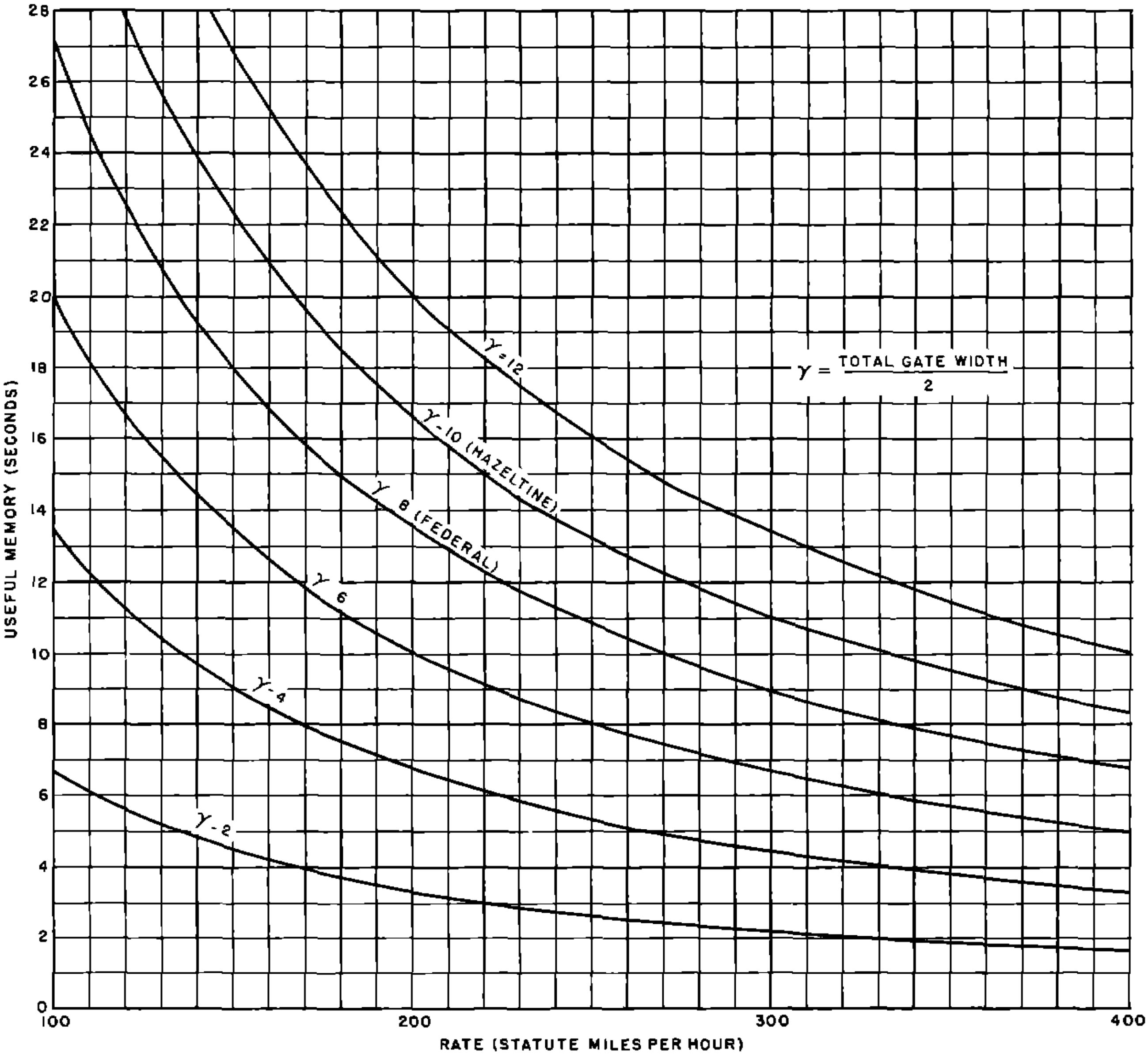


Fig 24 Memory versus Rate

a small percentage will arrive during the tracking gate duration If a sufficient number of the erroneous gated signals appear within a specified time, the interrogator will consider the legitimate signal recovered The random-gated signals will not persist and, when they disappear, the memory time will be re-initiated Effectively then, the danger of an excessive memory time in a densely populated DME system is that the memory will be further extended to some unreasonable value

The probability of detrimental re-initiation of memory for various traffic densities, various gate widths, and various memory times may be predicted statistically using probability methods Such an analysis reveals that under the worst possible conditions of traffic density, a memory time of six seconds is the maximum permissible It is believed that traffic densities of such a high order will not be realized for many years to come Consequently it is felt that 15 seconds is a logical compromise considering the various factors involved in selecting a specific duration of memory A minor adjustment can easily be performed, should future traffic conditions dictate a shorter memory period

ECHOES

Fig 9 illustrates how a multipath signal (echo) may cause needless interrogation of DME transpondors. The method for preventing such over-interrogation has been previously described In addition to the condition previously cited, echoes can lead, under certain conditions, to other effects detrimental to the proper operation of a DME system For example, in computing the random signals received by any DME receiver, a correction factor must be added to include multiplication of these signals by their own echoes This correction factor varies greatly, depending upon the general area in which the system is being operated Obviously, areas in which large objects (such as mountains and tall buildings) are numerous, are most conducive to the production of multipaths

A series of tests was conducted in the New York area in an effort to arrive at a quantitative figure for pulse increase due to echoes In this test, a pulse counter was employed to count the pulses received from an aircraft transmitter operating at a known repetition rate Under the worst conditions, the pulse rate count recorded was 35 per cent in excess of the actual pulse rate transmitted

In Fig. 25 is reproduced an oscillogram of an interrogator receiver output which shows typical multipath signals. Pulses a and b are those transmitted by the interrogator and, pulses c and d are the reply pulses from the transpondor Pulses e, f, g, and h are multipath signals of pulses a and b It will be noted that the amplitudes of e and f are near saturation

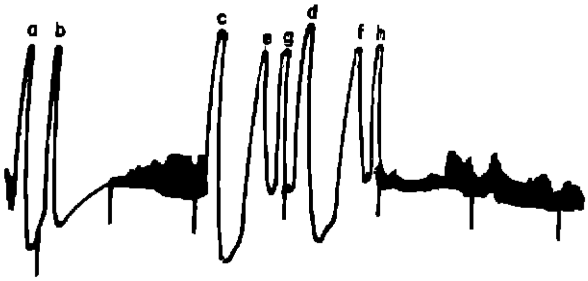


Fig 25 Echoes

The negative deflections of the traceline represent range markers spaced at 25 μ sec intervals

Fig 26 illustrates the effectiveness of the echo suppression circuit in the transpondor An incoming pulse and its associated echo are shown both before (Fig 26A) and after echo suppression (Fig 26B) In these illustrations which are exact tracings of actual photographs the range markers are spaced at 5 μ sec intervals In order to indicate relative amplitude before echo suppression, the receiver was not permitted to saturate on either pulse

GAP CODING

The type of identification coding employed in the present DME systems, though satisfactory for systems operating under low traffic conditions, is unsuitable under higher traffic density conditions This is particularly true in a pulse-multiplex system wherein the random pulse level is high Tests have shown that an improved and more reliable means of identification must be provided in future systems

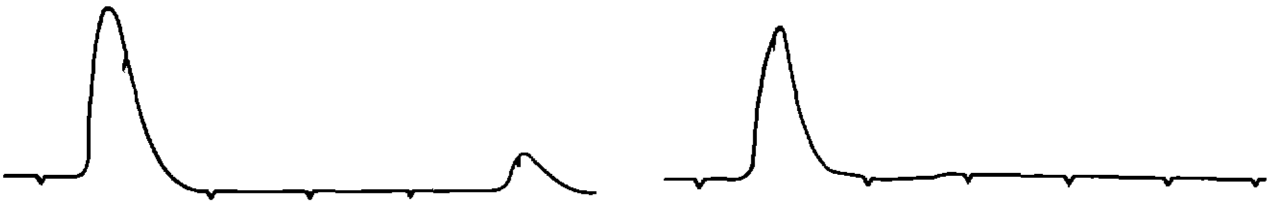
CONSTANT DUTY CYCLE TRANSPONDOR

The principle of operating a DME transpondor at full load at all times, such as the Federal constant duty cycle transpondor, has certain advantages, but, requires that the entire system operate under the worst possible conditions at all times A system should, of course, be capable of operation under such conditions, but the imposition of these conditions at all times is a needless demand Though satisfactory operation can be obtained in such cases, the efficiency frequently is reduced. For example, in a highly loaded system, the search time required is greater, the count-down is higher, and the memory time must be limited. Furthermore, operation in this fashion needlessly reduces tube life in the transpondor.

RELIABILITY

Most of the operating experience gained thus far has been with the Hazeltine pulse-multiplex system At the present time there are only limited data available with respect to the Federal system

Several thousand hours of operation have been experienced at the Technical Development and Evaluation Center with both interrogators



(A) BEFORE ECHO SUPPRESSION

(B) AFTER ECHO SUPPRESSION

Fig 26 Received Signals

and transpondors of the pulse-multiplex system During these periods, particularly after the first few hundred hours of operation, equipment breakdown was relatively infrequent The most frequent cause of faulty operation was tube failure. The most critical tube in the system appears to be the Type 3C37 tube employed as the transmitting oscillator for the transpondor, the same tube which is employed in the Federal transpondor The average life of these tubes has been disappointingly low, on the order of 250 - 500 hours Development of a more reliable tube is definitely indicated

Experience gained as a result of operational failures will be extremely valuable in the design of production equipment intended for continuous and unattended operation as a navigation aid Indications are that DME equipment which will compare favorably in operational stamina with existing well-established airway facilities will soon be available

TRAFFIC HANDLING CAPACITY OF PULSE-MULTIPLEX SYSTEMS

It was previously pointed out that the extent to which DME channels may be multiplexed on a single frequency has certain limitations[9] In designing a pulse-multiplex DME system, the designer must make certain that these limitations are not exceeded For a given set of parameters any pulse-multiplex system has a limited traffic handling capacity, beyond which point the service provided becomes unsuitable

[9] Hazeltine Electronics Corporation, Report No 2059W, "Traffic Handling Capacity of Distance Measuring Equipment Using 'Paired Pulse' Channeling," August 1947

The following factors determine the traffic handling capacity of a DME system

(1) Random pulse interference, commonly referred to as "fruit"

(2) The ratio of replies to interrogations required for proper operation of the interrogators, commonly referred to as "count-down"

Item 2 is largely dependent upon item 1 Each time the transpondor is interrogated, a "dead time" or "suppression time" is initiated which, until its expiration, prevents the transpondor from accepting further interrogations This dead time is generally of the order of 100 μsec Obviously a certain percentage of aircraft interrogations will arrive at the transpondor during this period The total dead time per second of a transpondor is equal to the product of the replies per second and the duration of an individual dead time The transpondor count-down is the percentage of the total time that the transpondor is dead The reciprocal of this relation is frequently referred to as the transpondor efficiency, i e, the percentage of replies to interrogations It follows that the greater the rate of interrogation of the transpondor, the higher the value of count-down The rate of transpondor interrogation increases as the product of the aircraft interrogation rate and the number of interrogating aircraft In a pulse-multiplex system, the total number of pulse pairs transmitted on a given frequency must be multiplied by the number of modes per frequency The count-down values of a given transpondor in such a system, may be increased over that created by its own associated aircraft by virtue of the fact that aircraft interrogating other transpondors sharing its frequency, also may be within its line-of-sight coverage These "parasite" aircraft, operating on the shared frequency, will transmit paired pulses with improper spacing, however, there exists

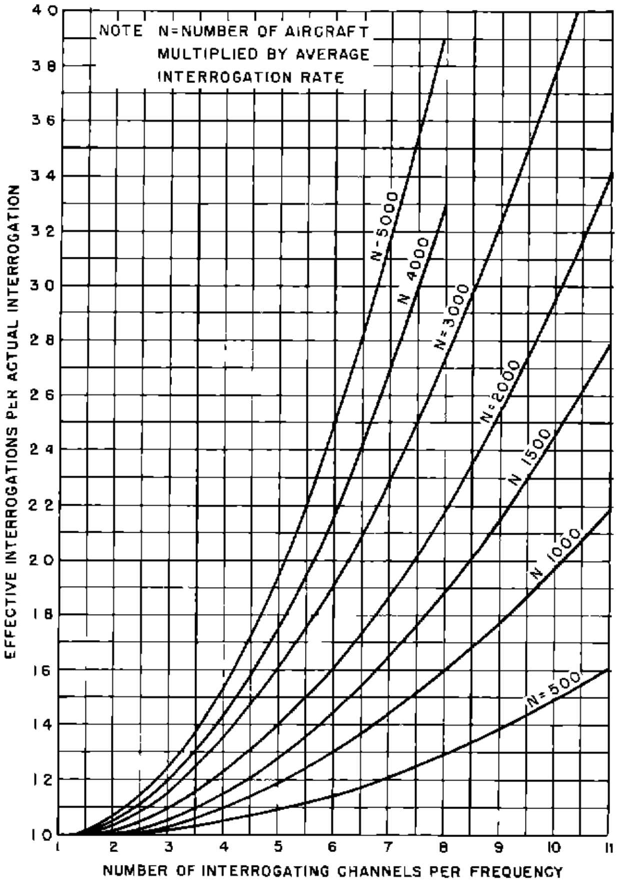


Fig 27 Increase in Effective Interrogations as a Result of Random Formation of the Proper Mode

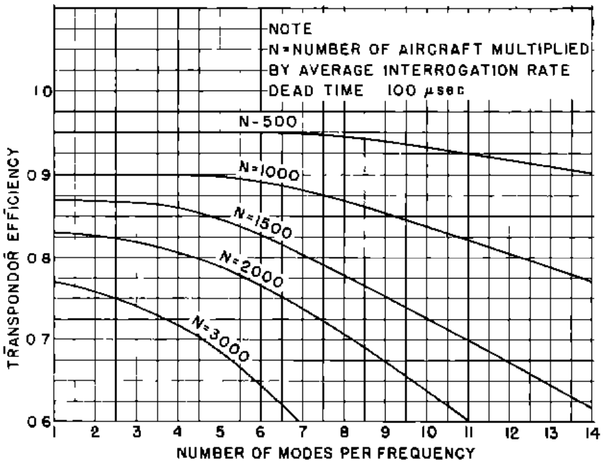


Fig 28 Variation of Transpondor Efficiency with Number of Modes and Number of Interrogations

a probability of these random interrogations overlapping to create pulse-pairs of the proper spacing This probability increases with the total number of interrogations If there is no limit on the number of aircraft operating within the system, the count-down of the transpondor may well reach a value beyond which the aircraft interrogator will not operate properly Fig 27 illustrates how the effective interrogation rate increases with the number of interrogating aircraft and the number of modes employed per frequency

Interrogators in modern DME systems are capable of proper operation with beacon efficiencies of 67 per cent (count-down 33 per cent) The designer must then take care to provide that the transpondors will be capable of operation at efficiencies no lower than 67 per cent with the maximum anticipated traffic Fig 28 illustrates how transpondor efficiency varies with the interrogation rate and the number of modes per frequency

In addition to its effect on the traffic handling capacity, the fruit level also is a determining factor in the selection of search and memory time

INTERNATIONALLY STANDARDIZED 100-CHANNEL DME SYSTEM

In order to meet the operational requirement for 100 discreet DME channels, expansion of the techniques employed in implementation of the 50-channel systems has been necessary

The practicability of both the high-stability technique, permitting 2.5 Mc frequency separation, and the pulse-multiplex technique having been established, the chief problem was to determine to what extent each of these methods should be employed In order to conserve frequency spectrum, the decision was made by RTCA Committee SC-40 that, the pulse-multiplex technique be extended to provide ten modes per frequency Thus, by employing a total of 20 frequencies (ten for interrogation and ten for reply), 100 channels may be provided within a total spectrum of approximately 50 Mc

Since contraction of the entire system into 50 Mc dictates the use of high stability transmitters and receivers, it is a necessary requirement that only narrow-band receivers be employed In order to obtain effective receiver response curves of the quality required, some means of sharpening the characteristic broad response to pulse signals must be employed In order not to preclude the use of the spike eliminator circuit, the duration of the transmitted pulse has been increased to 2 5 Mc Proper operation of the spike eliminator requires that the pulse width in microseconds be approximately three times the reciprocal of the if bandwidth in megacycles per second

In order to provide the ten modes required, it is obvious that longer delay lines must be employed The actual value of the ten delays to be employed are contained in Appendix I, which is the new system specification as approved at the COM Division meeting of ICAO at Montreal, during January and February 1949 This specification contains all of the requirements agreed upon by SC-40 of the RTCA

It will be noted that the stability requirements have been somewhat relaxed The tolerances indicated are considered to be adequate for proper operation of the system

It should also be noted that each of the 100 channels still meets the requirement that it have no two of its three operating parameters in common with any other channel

The transpondor dead time specified in Appendix I may be reduced in high traffic density areas, by dividing the over-all dead time into several separate dead times with a total duration considerably less than that required if a single dead time is employed The dead time as defined in the specification is sufficiently long to embrace the suppressed time delay In practice it is not necessary that the transpondor be made incapable of interrogation during the entire suppressed delay period A relatively short dead time may be employed to prevent re-triggering of the transpondor by the echoes of an interrogating pulse pair and a still shorter dead time may be used following each transmitted pulse to prevent ring-around. During the intervals between these dead-times, the transpondor is capable of receiving and replying to interrogations By use of this technique, the effective dead time may be reduced to an average of approximately 75 μsec

Operation of the 100-channel system under fully loaded traffic conditions imposes a severe limitation on the means previously employed to provide identification coding The presence of fruit pulses from other transpondors during the period of gap-coding of any individual transpondor makes it difficult for the airborne unit to recognize the absence of signal

A means of identification coding is to be employed in the new system which involves the use of a binary-code A third pulse is to be transmitted by the transpondor following transmission of the two-pulse DME reply This third pulse will be delayed with respect to the second reply pulse by one of two specified intervals Two special gates in the interrogator will recognize the presence or absence of signal at these two specific intervals Presence of signal in one of these gates will be considered a mark, whereas presence of a signal in the other gate will be regarded as a space The identification coding sequence of the transpondor shall consist of 15 such transmissions, each one of approximately one-second duration Fifteen elements in a binary code will provide for any possible combination of a three-letter code Presentation to the pilot will be visual, quite possibly by means of an indicator consisting of three rotating drums and engraved with the letters of the alphabet

CONCLUSIONS

It has been shown that the determination of distance by means of time measurement is practical Equipment has been built and sufficiently tested to indicate that a distance measurement system based on these principles will be adequate to serve the demands of any foreseeable air traffic densities

Contracts for production equipment are to be awarded in the near future and such equipment should be in wide scale use within the next five years This schedule is in accordance with the RTCA SC-31 plan for implementation of the transition system. Furthermore, there is good reason to believe that distance measuring equipment as presently built will be adequate to serve suitably as a part of the ultimate air navigation and traffic control system as envisioned by SC-31 By compressing DME service into a relatively small portion of the total frequency spectrum allocated for the ultimate system, the way has been left open for the system designers to use considerable latitude

During the transition period, the DME

should serve admirably together with the parallel course computer[10] and the VHF omnirange in providing a means of air navigation which far surpasses any existing or earlier system with regard to both accuracy and traffic handling capacity This system will, of course, provide the same service under instrument conditions as under contact flight conditions

[10]CAA Technical Development Report No 83, "Initial Flight Tests and Theory of an Experimental Parallel Course Computer," September 1948

APPENDIX I

Development Specification For UHF Distance Measuring Equipment

1.
Introduction

1.1
The operational use of UHF Distance Measuring Equipment (DME) has been proposed for standardization in connection with Aids to Final Approach to Landing and Short Distance Aids to Navigation

1.2
In order at the earliest possible date to arrive at a completely definitive specification suitable for adoption as an essential part of the COT Annex, it is considered necessary to adopt a development specification The aim of this specification is to indicate the agreed broad lines along which the UHF DME will be developed An orderly evolution along these lines will eventually enable the production of the final specification

1 3
It is emphasized that the primary aim of the specification is to achieve the proper direction of development of DME along certain broadly agreed lines The status within ICAO of the specification must be such as to permit changes, if such changes appear to be necessary during the later stages of development

1 4
It should be noted that the development specification covering the UHF DME is the first example of its kind and it, therefore, creates a precedent which it is recommended should be considered for adoption as an accepted practice for future use

2
Development Specification for UHF Distance Measuring Equipment (DME)

2 1
General

2 1 1
This specification is for the purpose of guiding development of Distance Measuring Equipment (DME) with the view towards ICAO standardization It is not an ICAO Standard or Recommended Practice at this time.

2 1 2
This specification outlines the characteristics of the Distance Measuring Equipment The system is intended to indicate, continuously and accurately, in the cockpit, the distance of properly equipped aircraft from preselected ground reference points

2 1 3
The system comprises two basic equipments The first of these, the aircraft equipment, shall be referred to as the interrogator The second, which is the ground equipment, shall be referred to as the transpondor

2 1 4
In operation, interrogators will be used to interrogate transpondors, which shall, in turn, transmit to the aircraft replies synchronized with the interrogations, thus providing means for accurate measurement of distance

2 2
System Requirements

2 2 1
Channeling

2 2 1.1
The system shall be implemented completely within two frequency bands, 960-986 Mc and 1188 5-1215 Mc There shall be ten interrogation frequencies and ten reply frequencies, with 2 5 Mc separation between adjacent radio frequency assignments. Specific assignments shall be as follows

Interrogation Band
960-986 Mc

Channel	
1	963 5 first interrogation freq.
2	966 0 second interrogation freq
3	968.5 third interrogation freq
4	971.0 fourth interrogation freq
5	973 5 fifth interrogation freq
6	976 0 sixth interrogation freq
7	978 5 seventh interrogation freq
8	981 0 eighth interrogation freq
9	983 5 ninth interrogation freq
10	986 0 tenth interrogation freq

Reply Band
1188 5-1215 Mc

Channel		
00	1188 5	first reply freq
10	1191 0	second reply freq
20	1193 5	third reply freq
30	1196 0	fourth reply freq
40	1198 5	fifth reply freq
50	1201 0	sixth reply freq
60	1203 5	seventh reply freq
70	1206 0	eighth reply freq
80	1208 5	ninth reply freq
90	1211 0	tenth reply freq

There shall be a guard band of 2 25 Mc between 960 and 962 25 Mc and a guard band of 2.75 Mc between 1212 25 and 1215 Mc

2.2.1 2
Each interrogation frequency shall be paired with each reply frequency in order to obtain 100 discrete operating channels

2.2 1 3
Double pulses shall be employed for both interrogation and reply, to further insure non-interference between operating channels Ten discrete double pulse spacings shall be provided Each combination of interrogation spacing and reply spacing shall constitute a mode, and there shall be ten such modes The pulse spacings, measured from the leading edge of the first pulse to the leading edge of the second pulse, shall be

Mode	SPACINGS Interrogation (Microseconds)	Reply	Mode	SPACINGS Interrogation (Microseconds)	Reply
A	14	77	F	49	42
B	21	70	G	56	35
C	28	63	H	63	28
D	35	56	I	70	21
E	42	49	J	77	14

The transmitted pulses shall be of 2 5 Microseconds duration

2 2 1 4
The DME operating channels shall be established as follows

				VHF FREQ (M C)	0	1	2	3	4	5	6	7	8	9
				DME CHANNEL	1	2	3	4	5	6	7	8	9	10
					INTERROGATION									
				DME FREQ (M C)	963 5	966 0	968 5	971 0	973 5	976 0	978 5	981 0	983 5	986 0
LOCALIZER	108	00	REPLY	1188 5	A	B	C	D	E	F	G	H	I	J
LOCALIZER	109	10	REPLY	1191.0	D	E	F	G	H	I	J	A	B	C
LOCALIZER	110	20	REPLY	1193 5	G	H	I	J	A	B	C	D	E	F
LOCALIZER	111	30	REPLY	1196 0	J	A	B	C	D	E	F	G	H	I
OMNIRANGE	112	40	REPLY	1198 5	C	D	E	F	G	H	I	J	A	B
OMNIRANGE	113	50	REPLY	1201 0	F	G	H	I	J	A	B	C	D	E
OMNIRANGE	114	60	REPLY	1203 5	I	J	A	B	C	D	E	F	G	H
OMNIRANGE	115	70	REPLY	1206 0	B	C	D	E	F	G	H	I	J	A
OMNIRANGE	116	80	REPLY	1208 5	E	F	G	H	I	J	A	B	C	D
OMNIRANGE	117	90	REPLY	1211 0	H	I	J	A	B	C	D	E	F	G

(a) Note 1 Letters in this chart indicate modes, in accordance with the table in Para 2 2 1 3

(b) Note 2 Numerals 1-10 inclusive, arranged horizontally, designate DME interrogation R F channels, and numerals 00-90, arranged vertically, indicate DME reply R F channels, in accordance with Para 2 2 1.1

2 2 1 5
The requirements specified in Paragraphs 2 2 1 1, 2 2 1 2, and 2 2 1 3 permit assignment of three parameters to each operating channel, (1) Interrogation frequency, (2) Reply frequency, (3) Mode These three parameters were assigned in accordance with the following channeling principles in the chart in Paragraph 2 2 1 4

(a) No two operating channels shall have identical interrogation and reply frequency combinations

(b) No two operating channels shall have identical frequency-pulse spacing combinations for interrogation and reply

(c) No two operating channels shall have identical interrogation (or reply) radio frequencies so long as the reply (or interrogation) paths of the two channels have adjacent radio frequencies, unless both paths of both operating channels have different pulse spacings They should always be separated by at least 100 statute miles (160 Km) when used for enroute navigation

(d) Two operating channels with identical or adjacent interrogation or reply frequencies can operate together providing the other path (reply or interrogation) is separated by at least two frequency channels

(e) Two operating channels with both adjacent interrogation and reply frequencies should always be separated by at least 100 statute miles (160 Km) when used for enroute navigation

(f) The same operating channel shall not be repeated with less than 460 statute miles (738 Km) separation when used for enroute navigation and shall not be repeated with less than 100 statute miles (160 Km) separation when used with ILS facilities

2 2 2
Accuracy

2 2 2 1
The transpondor shall not contribute more than plus or minus 1 0 microsecond (approx 500 feet (153m)) error to overall system inaccuracy

2 2 3
Range

2 2 3 1
The reliable service range of the system shall be

(a) At least 45 statute miles (72 Km) at 1000 feet (305m) altitude when the transmission path is over any type terrain that does not place obstructions in what would otherwise be the optical path

(b) When used for enroute navigation, at least 230 statute miles (369 Km) at line of sight altitude

Specifications in 2 3 1 4, 2 3 1 8, and 2 3 1 10 have been drawn up on the basis of meeting these two requirements

(c) When used with ILS facilities, at least 50 statute miles (80 Km) at line of sight altitude Specifications in 2 3 1 4, 2 3 1 8, and 2 3 1 10 (b) and (f) may be varied so long as the above requirements are satisfied

2 2 4
Traffic Capacity

2 2 4.1
The specifications for the airborne interrogator enable it to operate in the presence of 2000 other aircraft within a square area 500 statute miles (800 Km) on a side The ground transpondor can be designed to handle 50 aircraft in the presence of 1950 other aircraft on the remaining 99 operating channels

2 2 5
Identification Coding

2 2 5 1
Identification coding capable of presenting three-letter combinations visually to the pilot shall be employed

2 2 5 2
Pulses which form a binary code shall be used to convey the identification letters This

binary code shall enable at least 16,000 unique code combinations to be transmitted

2 2 5 3
The overall time of transmission and display of the three-letter code shall be not more than 20 seconds The code shall be transmitted every 30 seconds

2.2.5.4
The binary code, consisting of mark and space elements, shall be accomplished by transmission of single pulses, at one of two predetermined spacings, after the normal DME reply pulses

2 2 5 5
The mark pulse shall be transmitted 10 5 microseconds after the second of the double pulse DME reply The space pulse shall be transmitted 24 5 microseconds after the second of the double pulse DME reply.

2 2 5 6
All DME transpondors shall be provided with binary code identification

2 3
Detailed Requirements

2.3 1
Transpondor

2 3 1 1
The frequency of the transpondor transmitter shall not vary more than plus or minus 200 Kc.

2 3 1.2
The tolerance on the transmitted pulse spacings from the transpondor (including identity) shall be not more than ±0 5 miscroseconds The tolerance on the duration of the pulses transmitted shall be not more than ±0 2 microseconds

2 3 1 3
Transmitted Pulse Spectrum (This data will be specified at a later date)

2.3.1.4
The Peak power output of the transpondor transmitter shall not be less than 33 db above 1 watt

2 3 1.5
The maximum transpondor transmitter pulse repetition rate in the absence of interrogation (squitter) shall not exceed 300 double pulses per second. This figure shall be reduced to less than 5 per cent of the total replies when the transpondor is fully loaded

2 3 1 6
The transpondor receiver frequency shall not vary more than plus or minus 100 Kc

2 3 1 7
The decoder tolerance in the transpondor shall be not more than ±0 5 microseconds

2 3 1 8
The transpondor receiver triggering level shall be at least 11 2 db below 1 watt

2 3 1 9
The reception band of the transpondor receiver shall be such as to accept pulses specified in 2 3 2 1, 2 3 2 2, and 2 3 2 3 The reception band of the receiver shall also be such that synchronous pulses 2 Mc from the desired center frequency will not result in operation of the triggering circuits unless the amplitude of the pulses is at least 50 db greater than the minimum required for operation in the desired channel

2 3 1 10
The transpondor antenna shall

(a) Radiate vertically polarized energy,
(b) Have at least 6 db gain over a 1/2 wave dipole,
(c) Radiate with minimum discrimination as to azimuth,
(d) Have a beam width at half power points of not less than 6 degrees in the vertical plane,
(e) Have means incorporated to reduce nulls in the vertical pattern up to 90 degrees,
(f) Have a feeder with less than 3 db feeder loss, including mismatch

2 3.1.11
The Specifications in 2 3 1 4, 2 3 1 8, and 2 3 1 10 (b) and (f) above may be varied so long as at least an equivalent field strength and triggering level are maintained

2 3 1 12
When the transpondor is associated with an ILS facility, a suppressed time delay (measured from leading edge of the second interrogation pulse to leading edge of the second reply pulse), adjustable between 115 and 84 microseconds, shall be incorporated in the transpondor to permit zero distance to be indicated at a point up to 15,000 feet (4575m) from the transpondor site When the transpondor is not associated with an ILS facility, the suppressed time delay shall be 115 microseconds but need not be adjustable

2 3 1 13
The system shall be capable of including a transpondor providing reliable service to at least fifty equipped aircraft in the presence of 1950 other aircraft distributed over the remaining ninety-nine operating channels

2.3 1 14
The transpondor "dead time" shall be such as to maintain a transpondor efficiency of at least 70 per cent at maximum duty cycle The transpondor "dead time" should be the suppressed time delay plus 10 microseconds after the last of the three transmitted reply pulses This provides an effective "dead time", including the pulse spacing separation of the transmitted interrogation pulses, of from 133 to 227 microseconds

2 3 1 15
The transpondor receiver gain shall begin to reduce appreciably at 90 per cent of maximum duty cycle and shall be at least 50 db down at maximum duty cycle Reduction of receiver gain between minimum duty cycle and 90 per cent of maximum duty cycle shall be not greater than 3 db

2 3 1 16
Means for at least 50 db rejection of all spurious responses including image and if responses shall be incorporated in the transpondor receiver This rejection shall be exclusive of that afforded by the antenna Means for adequate CW suppression shall be incorporated in the transpondor receiver Means for adequate echo (clutter) suppression shall be incorporated in the transpondor receiver

2 3 1 17
Transpondor local oscillator radiation shall be suppressed adequately

2 3 1 18
Radiation from the transpondor at radio frequencies other than the carrier band shall be suppressed adequately

2 3 1 19
Means shall be incorporated to protect the transpondor receiver against interference outside the DME band

2 3 2
Interrogator

2 3 2 1
The interrogator transmitter frequency shall not vary more than plus or minus 400 Kc

2 3 2 2
The tolerance on the transmitted pulse spacings from the interrogator shall be not more than ±1 0 microseconds The tolerance on the duration of the pulses transmitted shall be not more than ±0 2 microseconds

2 3 2 3
Transmitted Pulse Spectrum (This data will be specified at a later date)

2 3.2 4
The interrogator average pulse repetition rate shall not exceed 30 double pulses per second, based on 95 per cent of the time for tracking and 5 per cent of the time for searching.

2 3.2 5
The interrogator pulse repetition rate for searching shall not exceed 150 double pulses per second

2.3 2 6
The pulse repetition rate shall have a random variation of not less than plus or minus 1 per cent and not more than plus or minus 20 per cent

2 3 2 7
The decoder tolerance in the interrogator (including identity decoding) shall be not more

than ±1 0 microseconds

2 3 2 8
The interrogator shall be capable of successful search with transpondor 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 3 2 9
A suppressed time delay of 115 microseconds shall be incorporated in the airborne equipment (This is measured from the leading edge of the second interrogation pulse to the leading edge of the second reply pulse)