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REGAL TEST PROGRAM SUPPORT

22 APRIL 1964

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SYSTEMS RESEARCH AND DEVELOPMENT SERVICE

BY

ITT Gilfillan Inc.

Final Report, Contract No. FAA/BRD-245

REGAL TEST PROGRAM SUPPORT

22 April 1964

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ABSTRACT

This final report presents the engineering results of the REGAL test evaluation program conducted by the Federal Aviation Agency (FAA). The evaluation was performed over the period of March 1960 to June 1963 by FAA's National Aviation Facilities Experimental Center (NAFEC) in Atlantic City, New Jersey. The basic objective of the program was to determine the feasibility of the REGAL system, using an interferometer antenna, to provide airborne derived elevation angle and range data capable of providing accurate guidance for the purpose of landing aircraft. Comprehensive static and dynamic testing has revealed that REGAL has an elevation accuracy of 0.03 for all angles 0.25 above the mean ground plane and that the range techniques present the ability to approach within ±50 feet or 1%, whichever is greater, of the actual range. The latter part of the program was used to determine how well REGAL actually performed in a landing system. Over two hundred completely automatic landings were achieved using four different type aircraft, all equipped with different type landing computers and autopilots.

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1. PURPOSE OF REPORT

The purpose of this report is to document the results of the flight test support provided to FAA/NAFEC during the test evaluation of the REGAL System. The FAA/NAFEC test program covered a series of static and dynamic accuracy tests and full landing system evaluations. This report presents a description of the program and an engineering analysis of the available results. The analysis is not intended to overlap the FAA reportage but to emphasize engineering conclusions concerning the basic capabilities and limitations of the system. This type of report is felt to be essential in providing direction for possible system improvement and for design and evaluation of future systems.

REGAL stands for Range and Elevation Guidance for Approach and Landing. REGAL does not constitute a complete all-weather landing system by itself but rather defines a subsystem for providing accurate position information to a flight control system. The experimental REGAL equipment was procured by the FAA as the first step in the program to develop a common landing system. The function of this equipment was to demonstrate the technical feasibility of the REGAL technique and to serve as an experminental tool in demonstrating control of aircraft along flexible curved paths near the ground.

2. GENERAL FACTUAL DATA

This section contains a general description of the REGAL System, an enumeration of its major features, and an explanation of the special techniques employed.

2.1 System Principles

The REGAL System is based on the principle of air-derived position data. In this system, the aircraft carries certain equipment to enable the pilot to determine his position with respect to a reference source near the runway and to determine the appropriate control maneuvers for an optimum approach and landing. The air-derived-data type of landing system has advantageous features in comparison to a system where radar equipment on the ground determines each aircraft's position, calculates guidance commands, and telemeters these commands to the appropriate aircraft. Some of the features are:

a. There is no inherent limit to traffic handling capacity.
b. The system may be used simultaneously by multiple aircraft following different paths.

c. The system may be used simultaneously by multiple aircraft types with different speeds and control characteristics.
d. No data link or communications system is required, eliminating the attendant identification problems.
e. The pilot may monitor performance and make decisions affecting safety.
f. The system is flexible for changing paths or for manual operation in case of emergency.
g. A single system will serve for simple instrument low approach or for sophisticated fully automatic landing, depending on complexity of airborne equipment.
h. There is no requirement for ground operators.

Based on the principle of air-derived data, the system is designed to use a scanning-beam, ground-reference transmitter which effectively generates a position-reference grid in the approach air space. The airborne equipment consists of a reciever-converter group containing demodulators to extract position data, and a flightpath control computer. The system uses a simple one-way transmission of electromagnetic energy which results in the following additional technical features:

a. One-way transmission of angle data results in improved range performance (greater than 10 miles).
b. Radar scintillation is non-existent and angle data is essentially noise-free.
c. Rain echo is not a factor in heavy-rain operation.
d. No search or acquisition problems exist for angle data.
e. Ground system equipment is simplified.

The REGAL system provides the aircraft with polar-coordiante position information (angle and range) in the elevation plane. This information is referenced to the ground transmitter which is located adjacent to the runway between 2000 and 3000 feet from the runway threshold.

To define completely the aircraft's position with a third data coordinate, azimuth angle information will be provided in future development and referenced to a localizer transmitting system site at the far end of the runway. The siting will be relatively similar to that of the current ILS localizer equipment. The location of the azimuth transmitting equipment at the far end of the runway will provide lateral control of the aircraft during the full rollout.

Elevation-angle data is supplied to the aircraft by a narrow fan-shaped beam of microwave energy which is scanned five times per second to cover the entire approach air space. The beam is modulated with pulse-coded signals, which define the instantaneous beam angle. The airborne receiver reads out the value of the modulated angle data at the instant the scanning beam is pointing directly at the aircraft. This yields a measurement of the elevation of the aircraft with respect to the ground equipment with an accuracy of 0.05 degree, at any angle between 0.25 degree and 20 degrees above the ground.

The REGAL airborne equipment includes a ranging system similar to DME which interrogates the ground equipment immediately following the receipt of angle data. A range reply, which is interlaced with angle data, is transmitted from the ground, and a tracker in the airborne unit measures the range. Accuracy of the range measuring system is better than ±50 feet or one percent of range, whichever is greater.

2.2 Special Techniques

The REGAL system incorporates a number of special techniques which overcome the technical problems of providing data with a very high order of accuracy at the short ranges and low altitudes associated with the touchdown region.

One technique is the use of an interferometer type antenna system. The antenna pattern, shown in Figure 2-1, has a very narrow beamwidth and a sharp interference null at its center. At close ranges (in the Fresnel region), where the beam of a conventional antenna is severely defocused, and at low altitudes where the beam of a conventional antenna is distorted by ground reflections, the REGAL system accuracy is preserved because the null in the antenna pattern is well defined and undistorted. The use of the interferometer technique also simplifies the task of the REGAL airborne equipment which must identify the beam center in the presence of ground reflections, because it is necessary only to determine the center of a narrow null whose width is within the system accuracy specification of 0.05 degree.

Another technique employed in the REGAL ground equipment is the use of an antenna which scans in a downward direction only. This feature insures that the antenna beam will always pass through the aircraft before it intercepts the ground. The airborne reciever can thus readily discriminate against ground-reflected signals by accepting only the first-received information in each scan cycle.

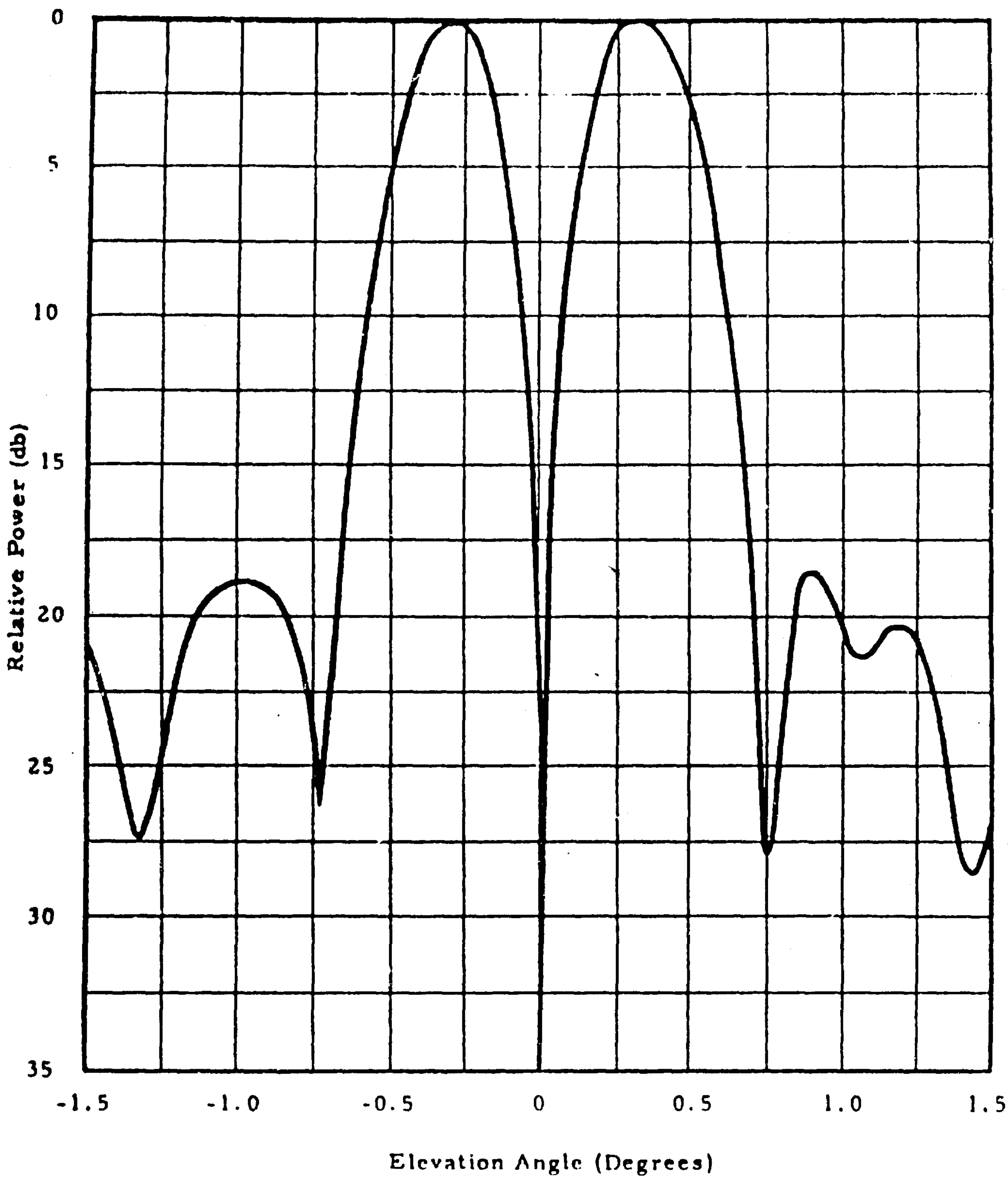


Figure 2-1. REGAL Antenna Pattern

A scanning beam type landing system must transmit the angle data, denoting the instantaneous beam elevation, with a very high degree of accuracy and stability. The REGAL system uses a combined serial and parallel digital data code to achieve an elevation data accuracy of 0.02 degree over the full scan range of -0.8 degree to 20 degrees. The format of the present REGAL angle data code is shown in Figure 2-2. The code consists of seven pulse code groups representing the coarse data and a series of pulse pairs which represent the fine data. The six most significant bits of the message are decoded in essentially parallel form from the seven pulse code group. The four least significant bits are decoded in serial form by counting the pulse pairs. The digital code used in REGAL, together with several self-checking features, provides extemely high data stability and reliability.

The REGAL ranging system is based on principles very similar to DME. However, by combining the ranging and angle system in REGAL the following unique features are obtained:

a. Ranging takes place at high microwave frequencies where wide channel spacing, and consequently the use of narrow pulses, is practical. (REGAL uses a 0.25 usec pulse width compared to 2.0 usec used in DME.)
b. Utilization of a high gain ground antenna (more than 25 db) minimizes requirements for airborne transmitting power.
c. By ranging only when the ground antenna is pointed at the aircraft, there is no interference between aircraft at different angles.

2.3 Equipment Description

A brief description of the REGAL equipment is given here to the block diagram level. A complete description of the system, including schematics and theory of operation, is given in the handbook of instructions for the REGAL transmitting set and the handbook of instructions for the REGAL receiver-converter group (references No. 1 and 2).

The REGAL equipment should be classed as experimental equipment designed for the objectives of the immediate program. As such, it does not necessarily reflect the optimum specifications for a final landing system. Design was also directed toward equipment which could be available for the flight test program at an early date, and only minor emphasis was placed on reliability and maintainability.

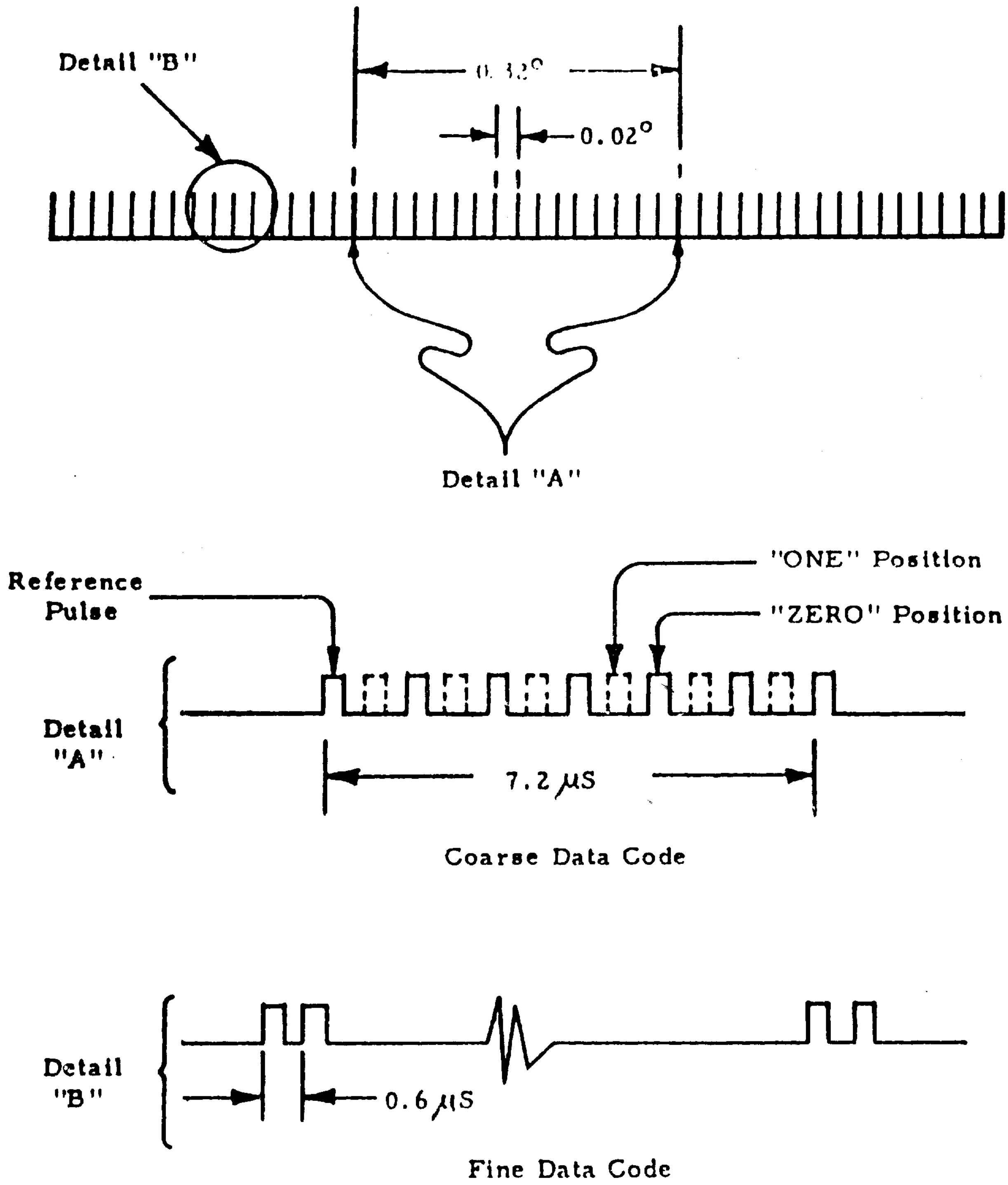


Figure 2-2. REGAL Angle Data Code Format

The REGAL system consists of two major groups of equipment: the REGAL transmitting Set and the REGAL Receiver-Converter Group.

2.3.1 REGAL Transmitting Set. - The REGAL transmitting set consists of an antenna system which includes the scanning drive mechanism and data take-off units, a transmitter-modulator group which includes a data encoder, a multiple-pulse X-band transmitter, and a receiver. The ground equipment is shown in Figure 2-3.

A functional block diagram of the REGAL transmitting set is shown in Figure 2-4. The elevation angle code is derived from precision electro-optical data take-off units, shown in Figure 2-5, in the form of a series of coarse and fine data pulses. The encoder performs parity checks, accumulates the data in a register, and generates the correct pulse code groups. A hard-tube pulse modulator and magnetron transmitter produce the X-band angle-data signals. Range interrogations from an aircraft, consisting of pulse pairs with a 0.9 usec spacing, are received in a conventional microwave receiver which is tuned 90 mc away from the transmitter frequency. After the interrogations are decoded, a reply pulse is generated in the encoder unless angle data is being transmitted.

2.3.2 REGAL Transmitter Characteristics. - The design characteristics of the REGAL ground equipment are as follows:

FEATURE	CHARACTERISTIC
Frequency	X-band-9.00 to 9.16 kmc
Range	500 ft to 10 mi
Elevation Coverage	20.8°
System Accuracies:	
Elevation	0.05°
Range	± 50 ft or 1% of range
Antenna Characteristics:	
Type	16 ft linear array (two)
Scan (down-scan only)	$+20.0^{\circ}$ to -0.80°
Scan speed	5 scans per second (both antennas)
Scan time (active)	120 milliseconds

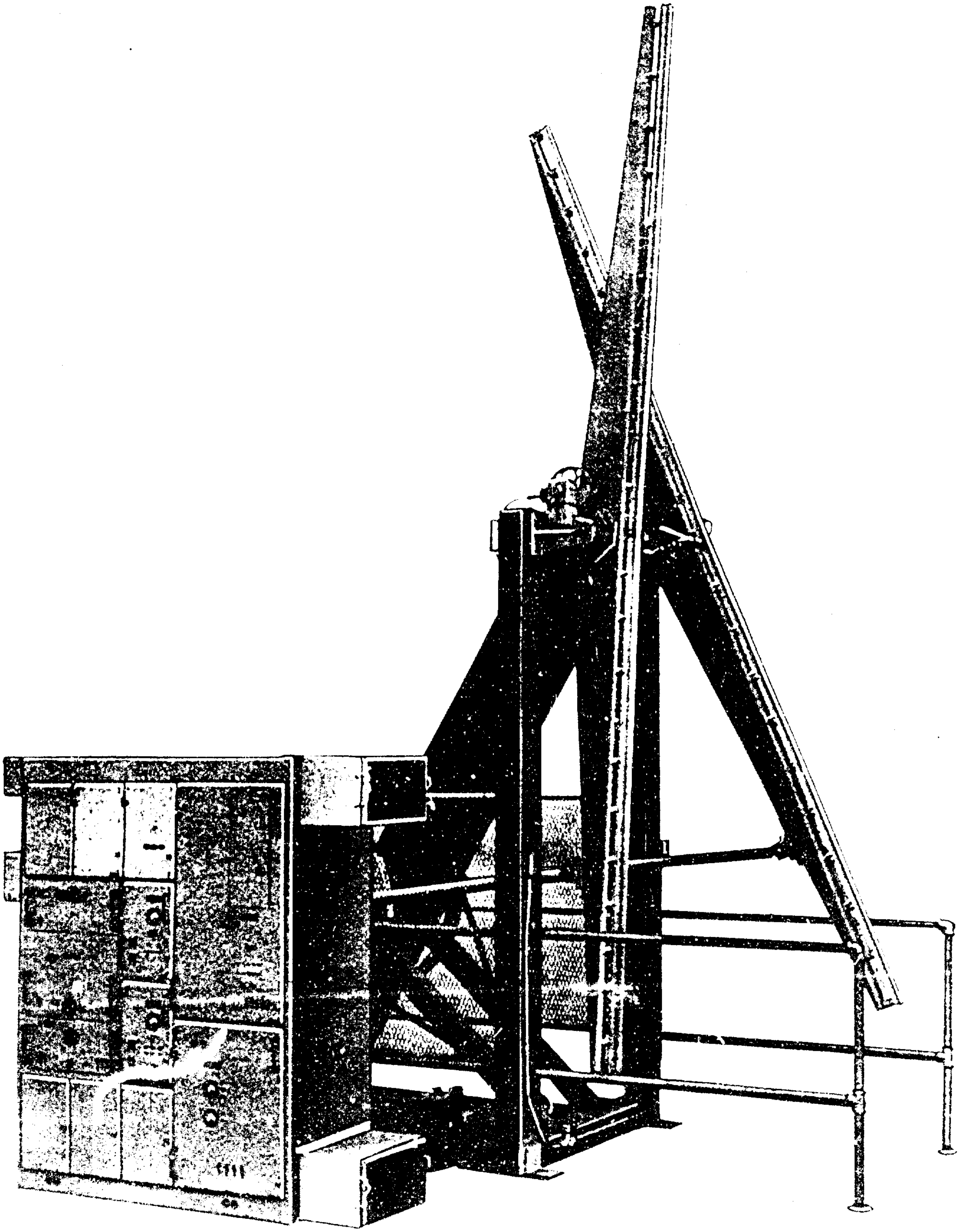


Figure 2-3. PEGAL Experimental Ground Transmitting Equipment

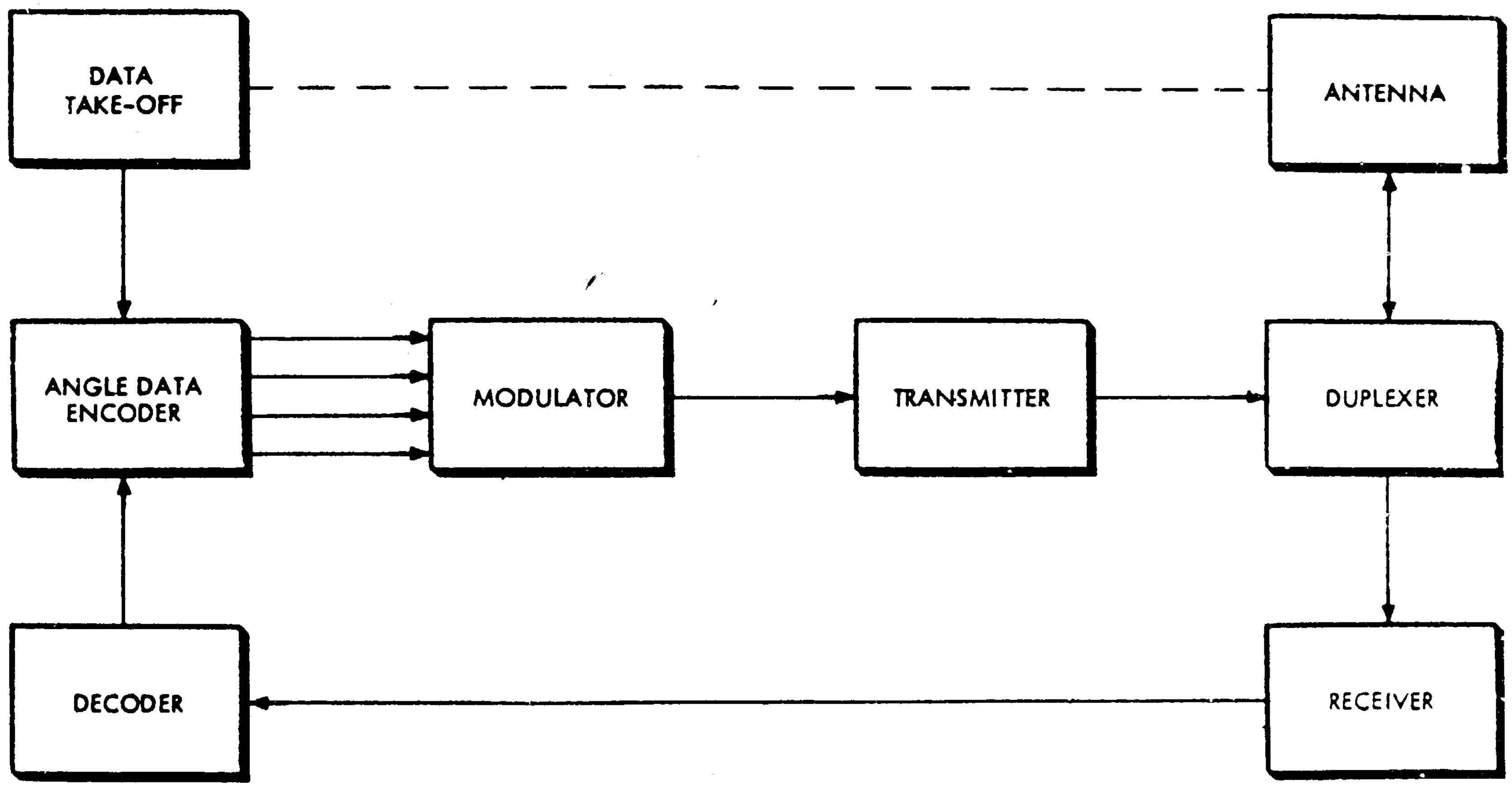


Figure 2-4. REGAL Transmitting Set - Block Diagram

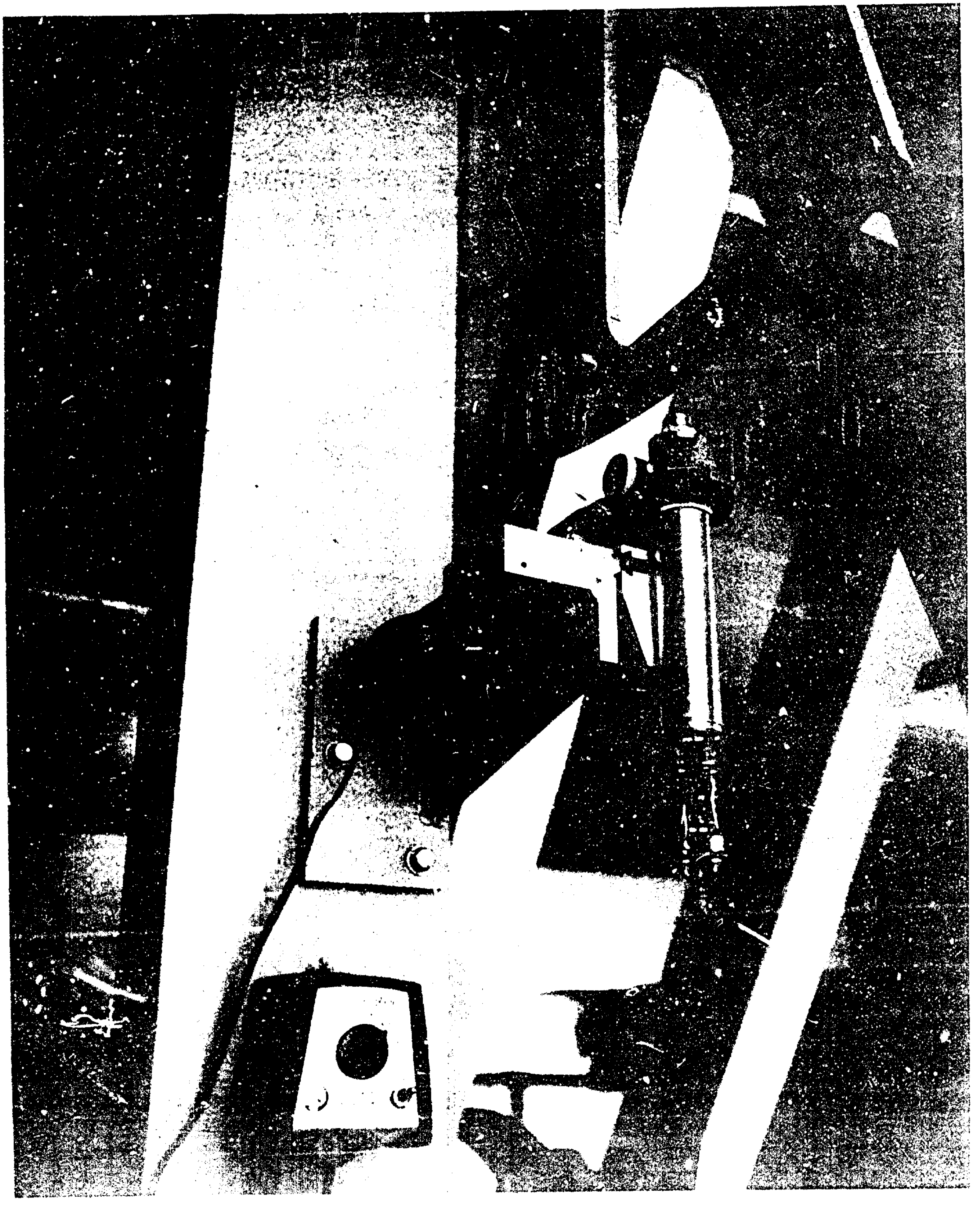


Figure 2-5. Angle Data Take-Off Unit

FEATURE	CHARACTERISTIC
Radiation pattern:	
Horizontal	45° at -3 db points
Vertical	Interferometer pattern less than 1.35° at -20 db, less than 0.113° null width at -10 db
Gain	25 db on each lobe
Modulator-Transmitter Characteristics:	
Nominal peak power output	150 kw
Pulse Characteristics:	
Pulse width	0.2 usec
Minimum pulse spacing	0.6 usec
Average PRF	10,000 pps
Receiver System Characteristics	
I-F bandwidth	15 mc
Sensitivity	-85 dbm for decoding of pair of 0.25 usec pulses spaced 0.9 usec apart

2.3.3 REGAL Receiver-Converter Group. - The REGAL receiver-converter group (airborne equipment) consists of: a completely transistorized receiver, decoder, digital-to-analog converter, range tracker, and ten watt pulse magnetron transmitter. This equipment (shown in Figure 2-6) receives the angle data from the ground equipment, and from it, determines the elevation angular position of the aircraft with respect to the touchdown point on the runway. The REGAL receiver-converter group also transmits interrogations to the ground equipment where a coded reply is interlaced with angle data and transmitted back to the airborne equipment for range-determination purposes. A functional block diagram of the REGAL receiver-converter group is shown in Figure 2-7.

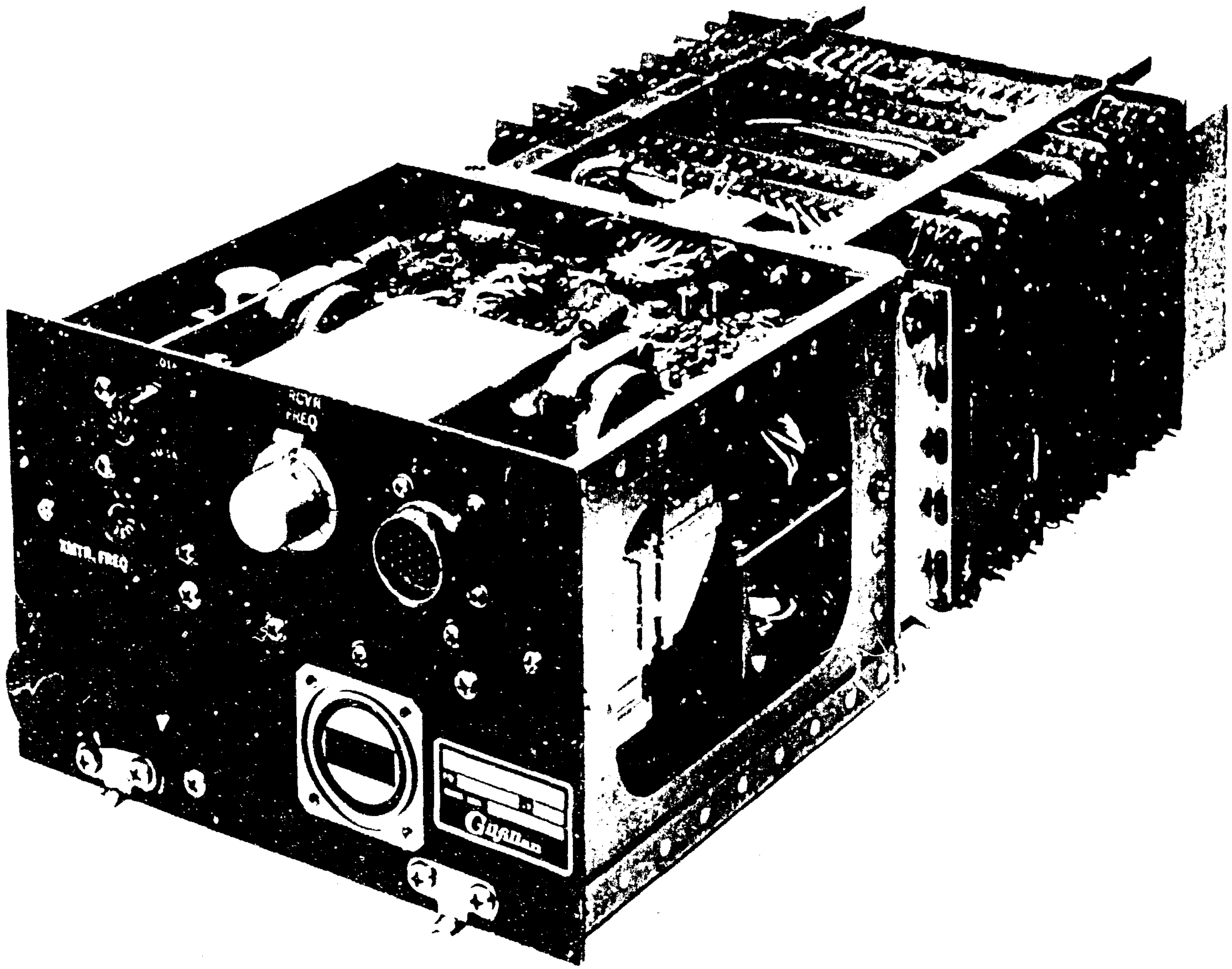
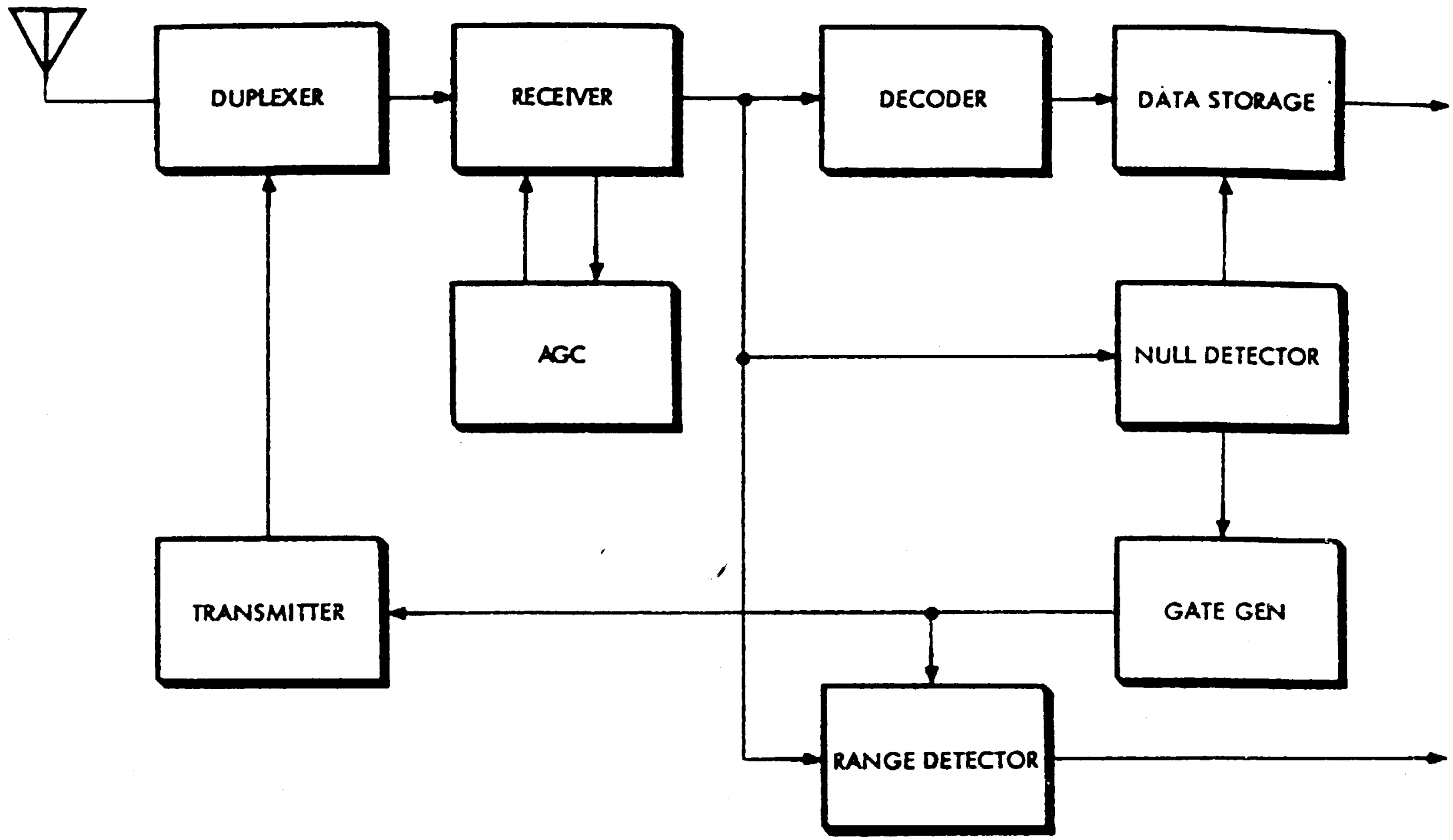


Figure 2-6. REGAL Airborne Receiver-Converter Group



Figui : 2-7. Receiver Converter Group–Block Diagram

Security-coded information is received by the antenna, detected directly into video and fed to a video amplifier, where it is amplified, standardized, and sent to the decoder. The decoder unlocks the security code and converts the information into digital form on a register. The digital information from the register is then sent to the digital-to-analog converter (data storage) and converted to an analog voltage for readout by means of meter displays. The automatic gain control circuit controls the average receiver gain so that the main beam of the ground antenna pattern is maintained at a relatively constant amplitude in the video output. Figure 2-8 shows a typical waveform of the received video as the ground antenna scans past the aircraft.

The beam-center (null) detector uses the dual-lobe envelope of the received signal to generate a series of gates for beam-angle detecting and range tracking. The first gate (a count gate) is open during the first lobe to allow the angle-reading decoder to accumulate angle data until the null occurs, and the second or tracking gate allows the range-determining function to interrogate the ground system during passage of the second lobe of the scanning beam. The interrogation consists of a dual pulse randomly timed for range tracking information. Approximately 15 asynchronous ranging interrogations are transmitted during the second half of the main beam. The range to the ground equipment is measured in the range detector. This subassembly contains a dc analog tracking loop. A narrow range gate prevents interference, or replies meant for other aircraft, from disrupting the tracker.

The receiver-decoder unit contains a high integrity "data-good" system. A data-good signal is generated only when the decoded angle data has passed several parity checks, a valid null has been received by the null detector, and the range detector is in track.

A number of details of the present REGAL system would probably be altered in a future operational equipment both because some of the experimental equipment parameters were chosen as a time expedient and because areas for improvement have been discovered. Some of the more significant changes would include:

a. A full serial digital data code, utilizing pairs of pulses with three spacing increments, would eliminate the need for the seven-pulse modulator and decoder, and would provide for additional parity and identification pulses.
b. The use of an alternate superhetrodyne airborne receiver would provide a range capability up to 40 miles in heavy rain.
c. Data resolution of approximately 0.01 degree.
d. Elevation angle coverage up to ten degrees will be satisfactory for almost all applications.

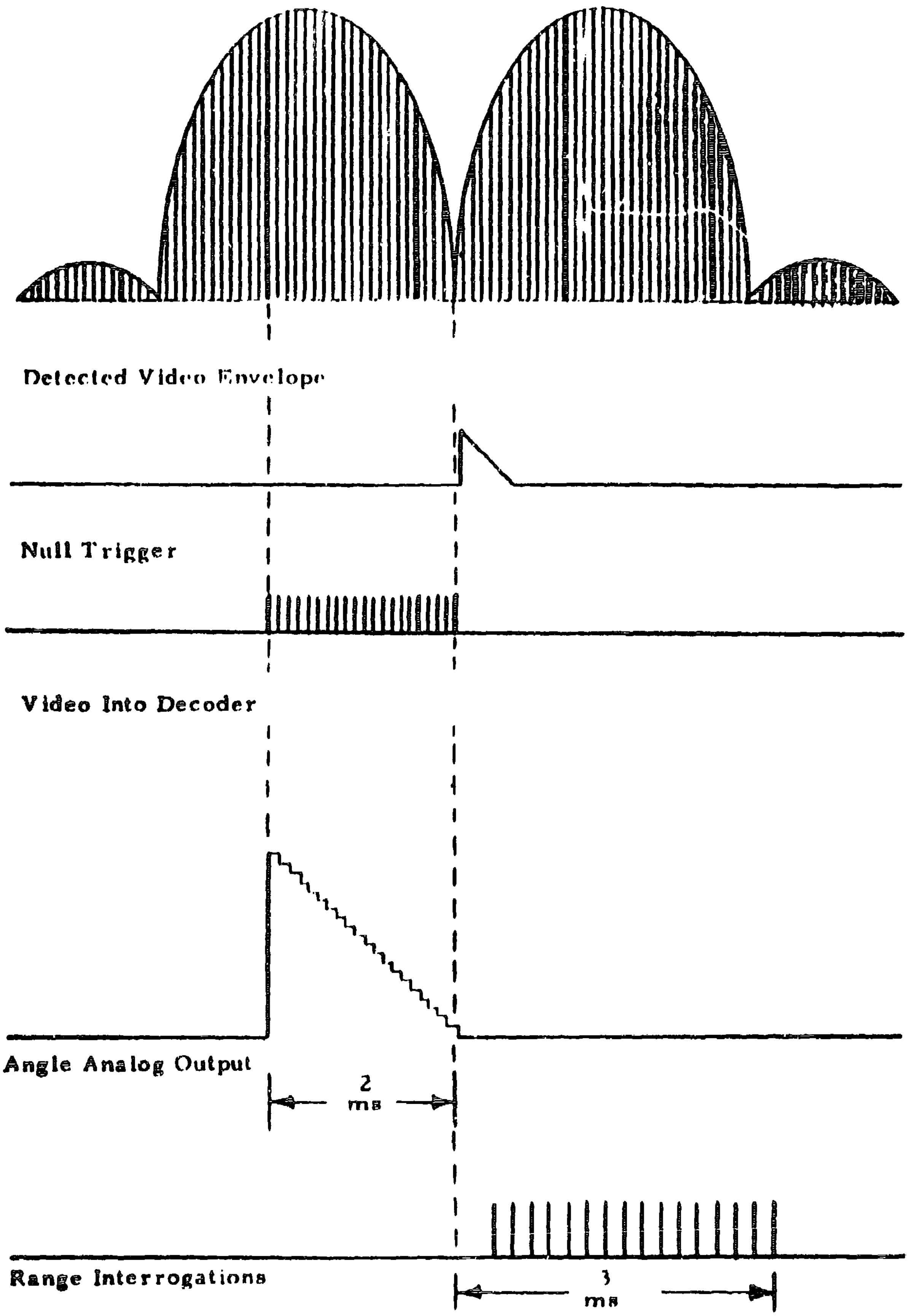


Figure 2-8. REGAL Airborne Receiver-Decoder Waveforms.

2.3.4 RECAL Receiver-Converter Characteristics – The design characteristics of the receiver-converter group units are as follows:

FEATURE	CHARACTERISTIC
Primary ac power	115-volts, 400-cycles, single-phase 0.35-amperes
Primary dc power	28-volts, 600-ma (remote turn-on operation)
Receiver sensitivity	-47 dbm for 14 db signal-to-noise ratio
Video bandwidth	3.0 mc
AGC control range	50 db
AGC time constant	5 ms attack, 1 sec decay
Video output level	9.0v peak
Transmitter power	5.0 w peak minimum
Transmitter pulse	Pair of 0.25-usec pulses spaced 0.90 usec apart

Characteristics of the data decoder include:

FEATURE	CHARACTERISTIC
Input Signal:	
Coarse data	7-pulse code group (6 bit pcm)
Conditions for decoding	Only one pulse present in position prescribed for each bit
Fine data	2-pulse code groups 0.6 usec spacing
Range data reply	Signal pulse synchronous with interrogation
Output Signal:	
Elevation angle data:	Analog voltage
Scale factor	0.90v/degree

FEATURE	CHARACTERISTIC
Range data:	+20° to 0.8°
Accuracy	0.025° rms
Range data:	Analog voltage
Scale factor	1.80v/n.mi
Range	500 ft to 10 mi
Accuracy	50 ft plus 1% range
Range interrogation:	
Pulses (PRF)	4,000 pulses/sec (approximately)

2.4 REGAL Coordinate Converter

In addition to the basic REGAL system three coordinate converter units were built by Gilfillan to facilitate the flight test program. Development of these units became necessary because of the need for diverse forms of input signals to flight path computers not directly available from a REGAL receiver.

The coordinate converter processes data output signals from the REGAL airborne receiver and provides a flexible set of inputs to a flight path computer and flight control system. The data signals from the REGAL equipment are position data signals in polar-coordinate form, referenced to the ground transmitter site as an origin. By converting this data to polar-coordinate data referenced to another hypothetical origin off the end of the runway, the utility of the basic REGAL data is greatly enhanced. If the new origin is considered to be the aiming point during the aircraft's approach, then the computation of the approach path becomes very simple. Also, the computation of a flareout path may be performed (with essentially the same control functions as used during the approach) by dynamically varying the position of the new data origin.

The coordinate converter was built as an experimental model suitable for airborne operation during the one-year flight test program and is not to be considered as applicable for use in a final landing system. The flexible set of data outputs provided by the coordinate converter was designed to facilitate a variety of flight path computation techniques, in addition to being used for instrumentation, or for cockpit display.

2.4.1 Physical Description. - The coordinate converter unit (Figures 2-9 and 2-10) consist of: thirteen plug-in chopper-stabilized operational amplifiers, three position servo units with plug-in amplifiers, and two regulated power supplies.

All the operational amplifiers are of etched-circuit construction and are directly interchangeable in the unit. The output resistors and computing circuit elements for each amplifier are mounted on circuit boards located on the underside of the unit chassis. One such board has been provided for each operational amplifier receptacle. All amplifier receptacles are interlock-wired so that amplifiers may be removed from the unit without damage to subsequent circuits or amplifiers.

The servo amplifiers are wired-circuit plug-in modules which are also interchangeable. The servo motor and potentiometer assemblies are mounted on supporting brackets located on the rear section of the main deck. The power supplies and associated transformers, rectifiers, filters and regulators occupy the extreme rear of the unit.

2.4.2 Functional Description. - The coordinate converter is capable of accepting aircraft position data from a REGAL receiver and provides polar coordinate data referenced to an arbitrary origin as a primary output. The range offset of this point of origin is variable in accordance with input analog voltage. Along with the primary output, the unit is also capable of providing the following:

a. Time rate of change of the position data signals.
b. Angular position errors referenced to an arbitrary glide slope angle which is defined by an input analog voltage.
c. Aircraft altitude over a range of 0 to 2500 feet.

Figure 2-11 is a functional block diagram of the coordinate converter. For purpose of clarity, only the computing elements are shown. It is to be noted that the computer may be essentially divided into three basic processes.

The first process involves REGAL elevation angle (γ), the extraction of its derivative ($\dot{\gamma}$), its coordinate transformation (γ_x), error calculation ($\Delta\gamma$), and transformed derivative ($\dot{\gamma}_x$). These tasks are performed by operational amplifiers number 1 through number 6.

The second process involves REGAL range (ρ), the extraction of its derivative ($\dot{\rho}$), coordinate transformation (ρ_x), and extraction of its transformed derivative ($\dot{\rho}_x$). These tasks are performed by operational amplifiers number 7 through 11.

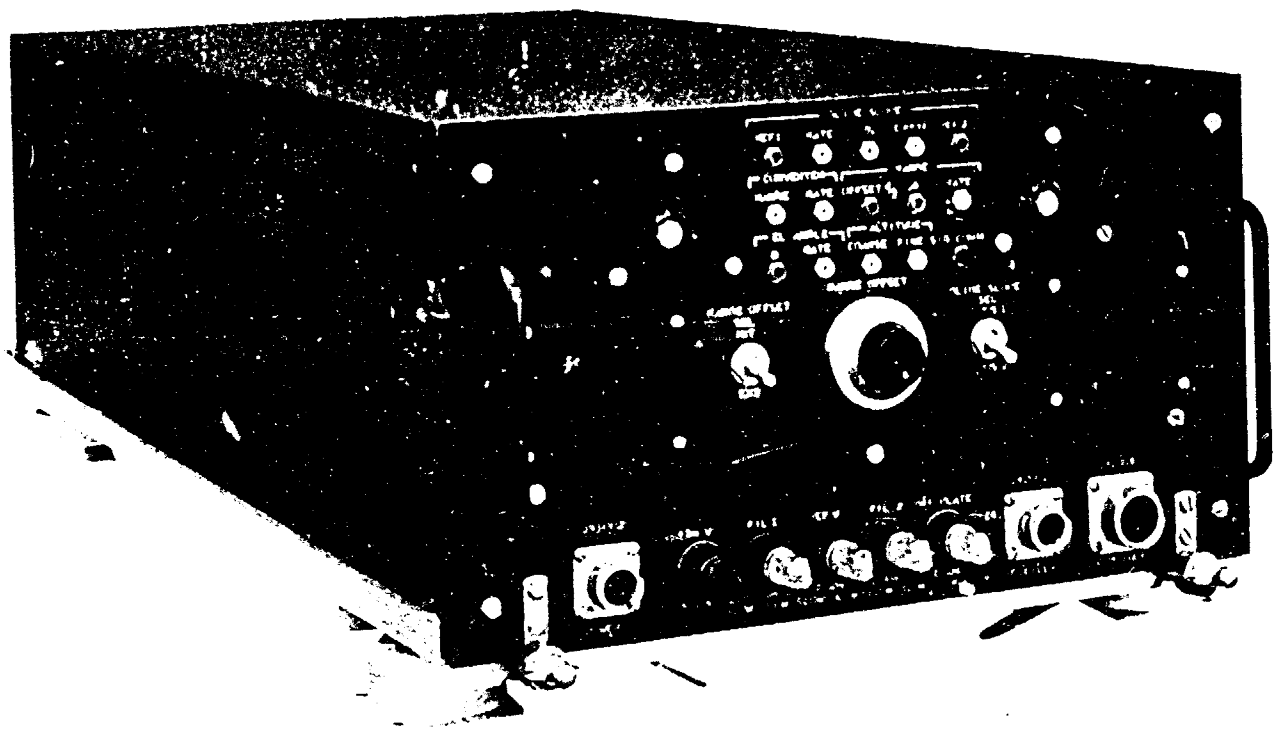


Figure 2-9. Coordinate Converter - Front View

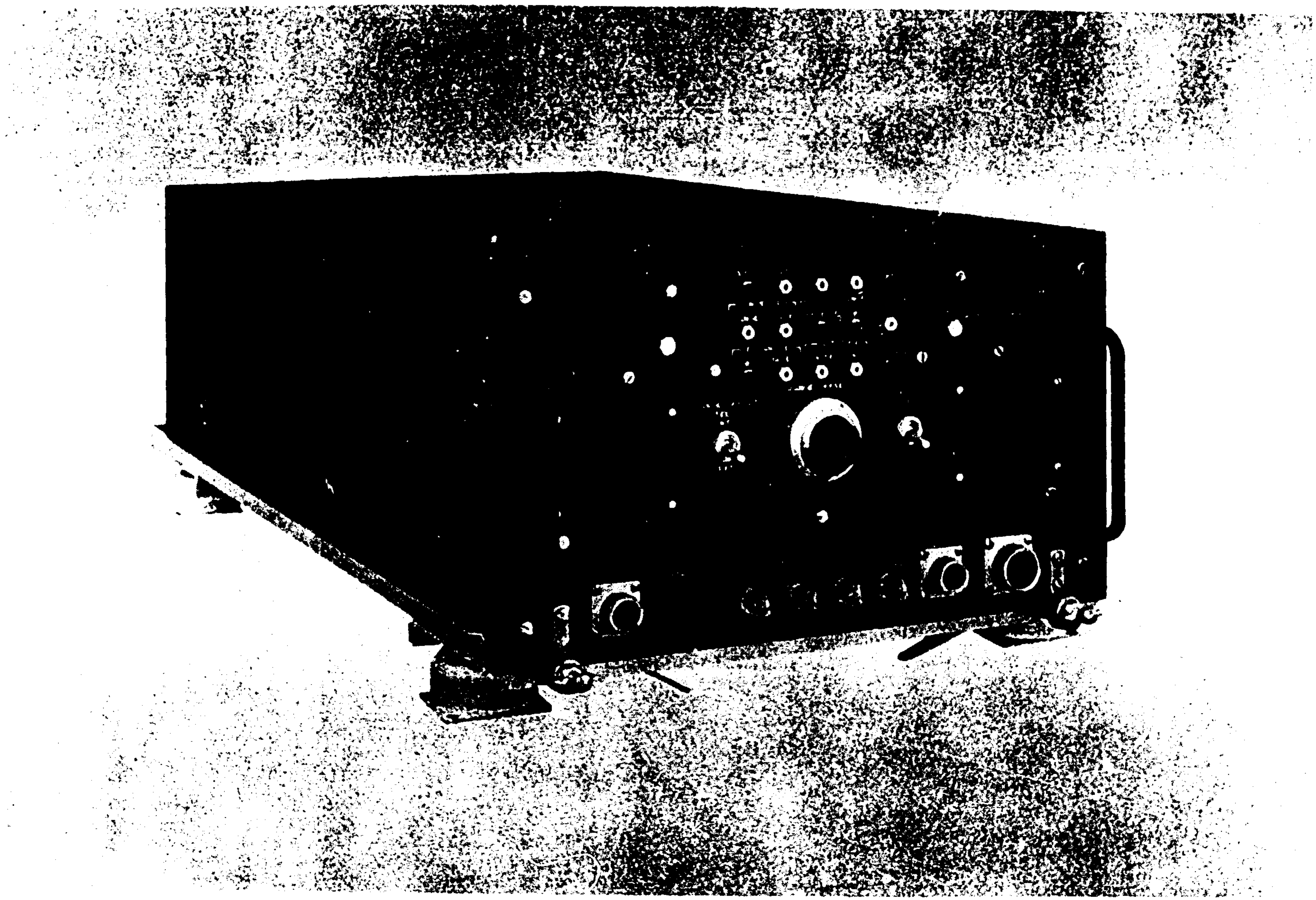


Figure 2-9. Coordinate Converter - Front View

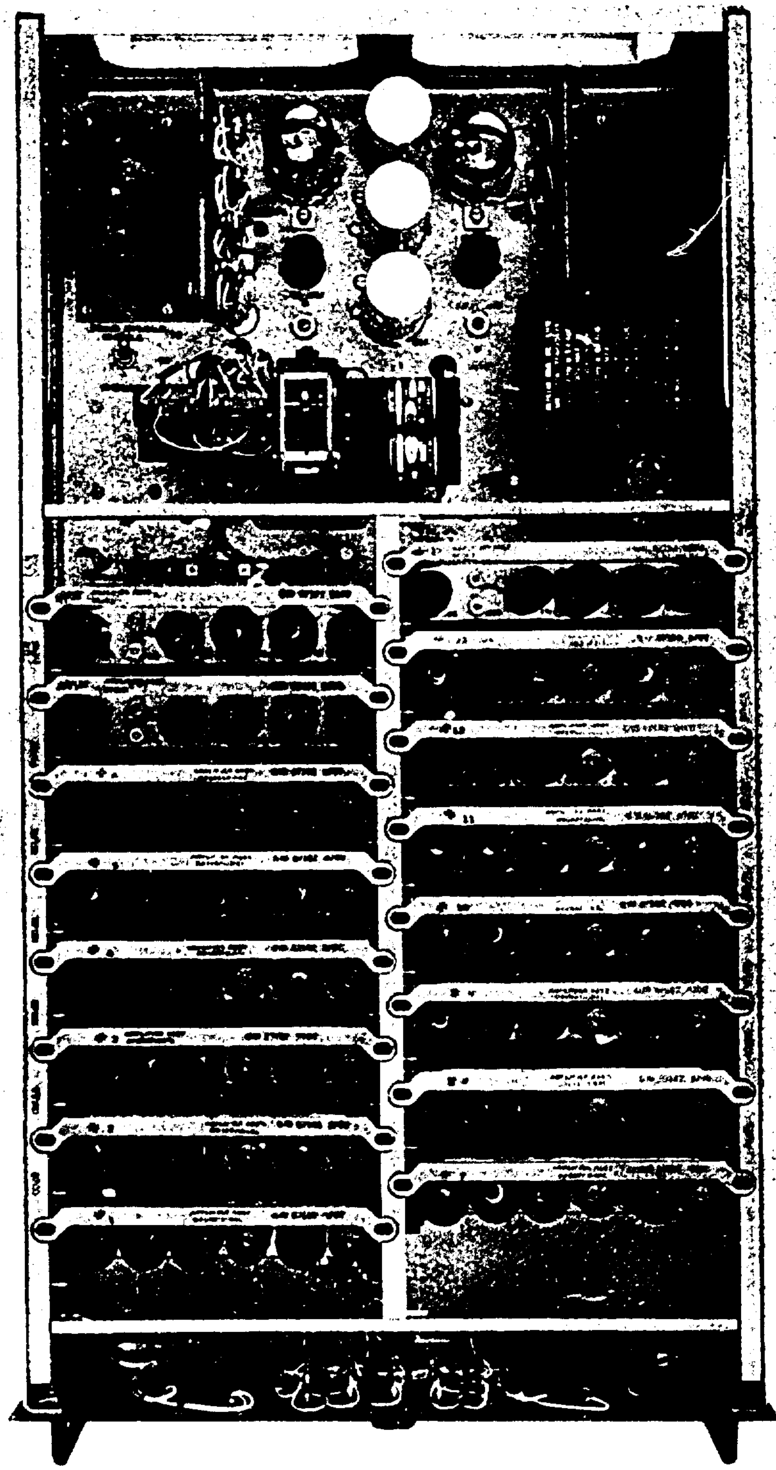


Figure 2-10. Coordinate Converter - Top View

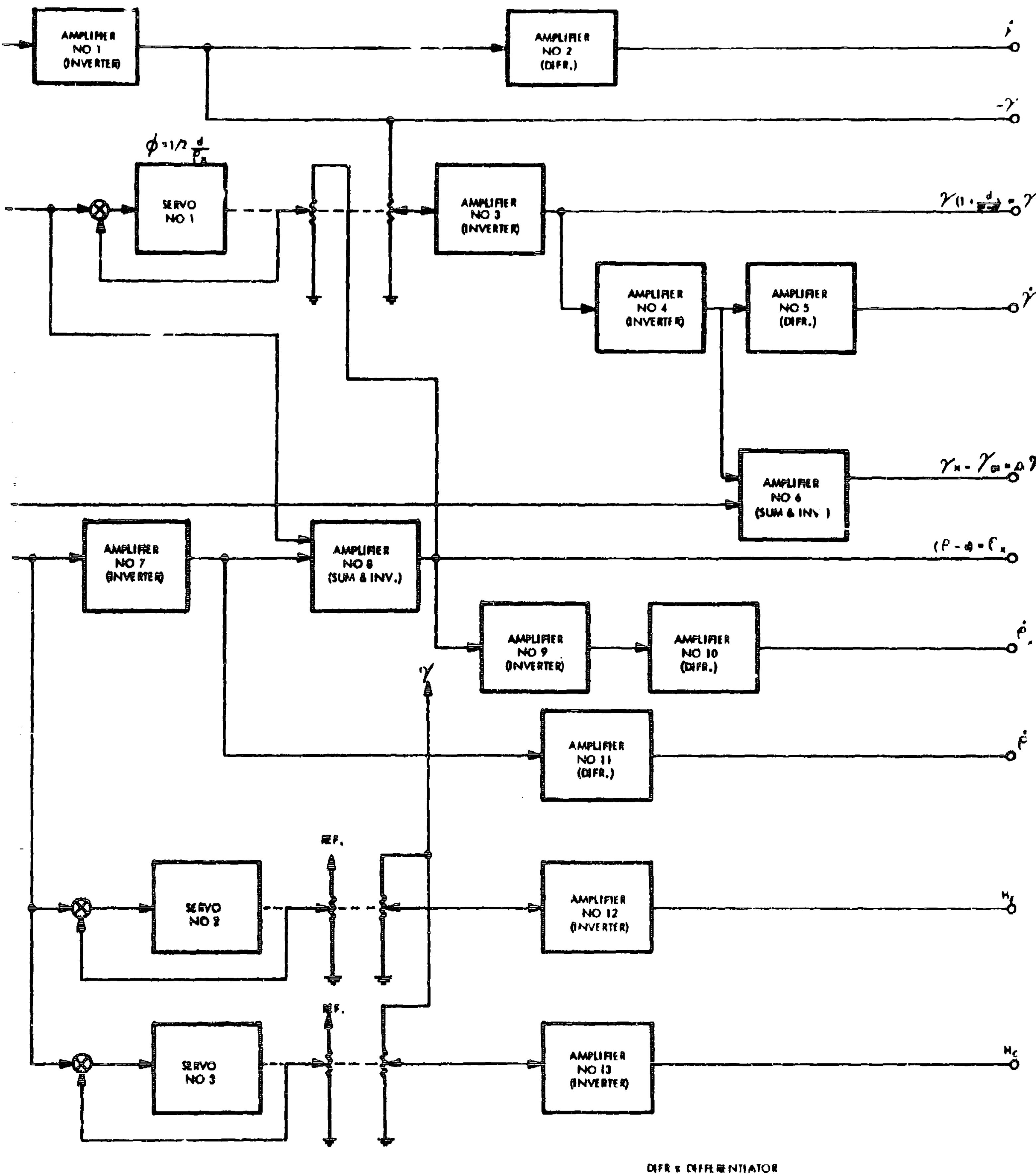


Figure 2-11. Coordinate Converter-Block Diagram.

Third process is altitiude computation, both coarse (H_c) and fine (H_f). This task is performed by servos number 2 and number 3, and operational amplifiers number 12 and number 13.

The above mentioned takes are described in further detail in the REGAL final engineering report previously submitted to FAA.

2.4.3 Coordinate Converter Characteristics. - The design characteristics of the coordinate converter input signals are as follows:

FEATURE	CHARACTERISTIC
Angle data	(from REGAL receiver) 0.9 volt/degree
Range data	(from REGAL receiver) 1.8 volt/6000 feet
Range offset (d)	DC analog voltage
Scale factor	0.1667 volt/1000 feet
Range	0 to 1.333 volts (0 to 8000 feet)
Glideslope reference (γ_{gs})	DC analog voltage
Scale factor	0.900 volts/degree
Range	0 to 20 degrees (0 to +18 volts)
Precision reference	Precision regulated dc voltage
Voltage	18.720 volts
Accuracy	$\pm$0.005 volt

FEATURE	CHARACTERISTIC
Coarse altitude (h_c)	DC analog voltage
Scale factor	0.04 volt/foot
Range	0 to 2500 feet (0 to 100 volts)
Computation accuracy	$\pm$10 feet
Fine altitude (h_f)	DC analog voltage
Scale factor	0.4 volt/foot
Range	0 to 250 feet (0 to 100 volts)
Computation accuracy	$\pm$1 foot
Converted range rate data (ρ_x)	DC analog voltage
Scale factor	25 volts/1000 feet/second
Range	$\pm$100 volts
Elevation angle rate ($\dot{\gamma}$)	DC analog voltage
Scale factor	25 volts/degree/second
Range	$\pm$100 volts

Characteristics of the output signals include:

Glideslope data (γ_x)	DC analog voltage
Scale factor	5 volts/degree
Range	0 to 20.0 degrees
Computation accuracy	$\pm$0.05 degree

FEATURE	CHARACTERISTIC
Converted range data (ρ_x)	DC analog voltage
Scale factor	1 volt/3000 feet
Range	500 feet to 60,000 feet
Computation accuracy	1 percent $\pm$25 feet
Glideslope error ($\Delta\gamma$)	DC analog voltage
Scale factor	10 volts/degree
Range	$\pm$50 ($\pm$50 volts)
Glideslope rate ($\dot{\gamma}_x$)	DC analog voltage
Scale factor	25 volts/degree/second
Range	$\pm$100 volts
Range rate ($\dot{\rho}$)	DC analog voltage
Sca e factor	25 volts/1000 feet/second
Range	$\pm$100 volts

2.5 References

1. Preliminary Handbook of Installation, Operation, and Maintenance Instructions for the REGAL Approach and Landing Sy tem Transmitting Set, Gilfillan Bros., Inc., 1959.

2. Preliminary Handbook of Installation, Operation, and Maintenance Instructions for the REGAL Receiver-Converter Group of the Approach and Landing System and the Performance Monitor Group, Gilfillan Bros., Inc., 1959.

3. REGAL Equipment Final Engineering Report, Gilfillan Bros., Inc.

3. DETAILED FACTUAL DATA

The REGAL equipment, which consisted of an experimental transmitting set and five airborne receiver-decoder units, was delivered to the FAA's National Aviation Facilities Experimental Center (NAFEC) in Atlantic City, New Jersey, in March 1960. Also delivered were three experimental coordinate converter units which provide a very flexible coupling between the airborne REGAL equipment and various instrumentation and flight control systems. Since that time, the FAA has been conducting a broad test program which included a determination of the position measuring capabilities of the basic REGAL equipment as well as tests of several flight control systems which employ REGAL information.

This section presents detailed data describing the test installations of ground and airborne equipment used during the REGAL test program at NAFEC. Also presented are the results of the static angle and range accuracy tests and the results of the dynamic accuracy and flight control tests.

3.1 Test Installations

During the course of the program, the REGAL ground transmitter set was sited at two different locations for different phases of the testing. The REGAL airborne receiver-decoders were installed in a mobile test truck and in four different aircraft. These installations were updated and modified in accordance with the testing objectives and instrumentation available.

3.1.1 Ground Equipment Installation. - For the initial static and dynamic accuracy test portion of the program, the REGAL ground transmitter set was sited close to the end of the primary instrument runway (runway 13). The site was chosen to minimize interference from a crossing runway and to achieve a touchdown point at a minimum safe distance from the threshold. The touchdown point conincided with that used by the AN/GSN-5 system, and also was within the coverage of the interim photo-theodolite system installation .

The REGAL equipment was sited adjacent to runway 13-31 (as shown in Figures 3-1a, and 3-1b), 2400 feet from runway threshold and 1200 feet behind the touchdown point. To provide for a longitudinal touchdown dispersion the lateral displacement of the REGAL system was approximately 280 feet from the centerline. This displacement assured as complete an azimuth coverage of the ±500 foot touchdown zone as possible.

Figure 3-1a. NAFEC REGAL Location

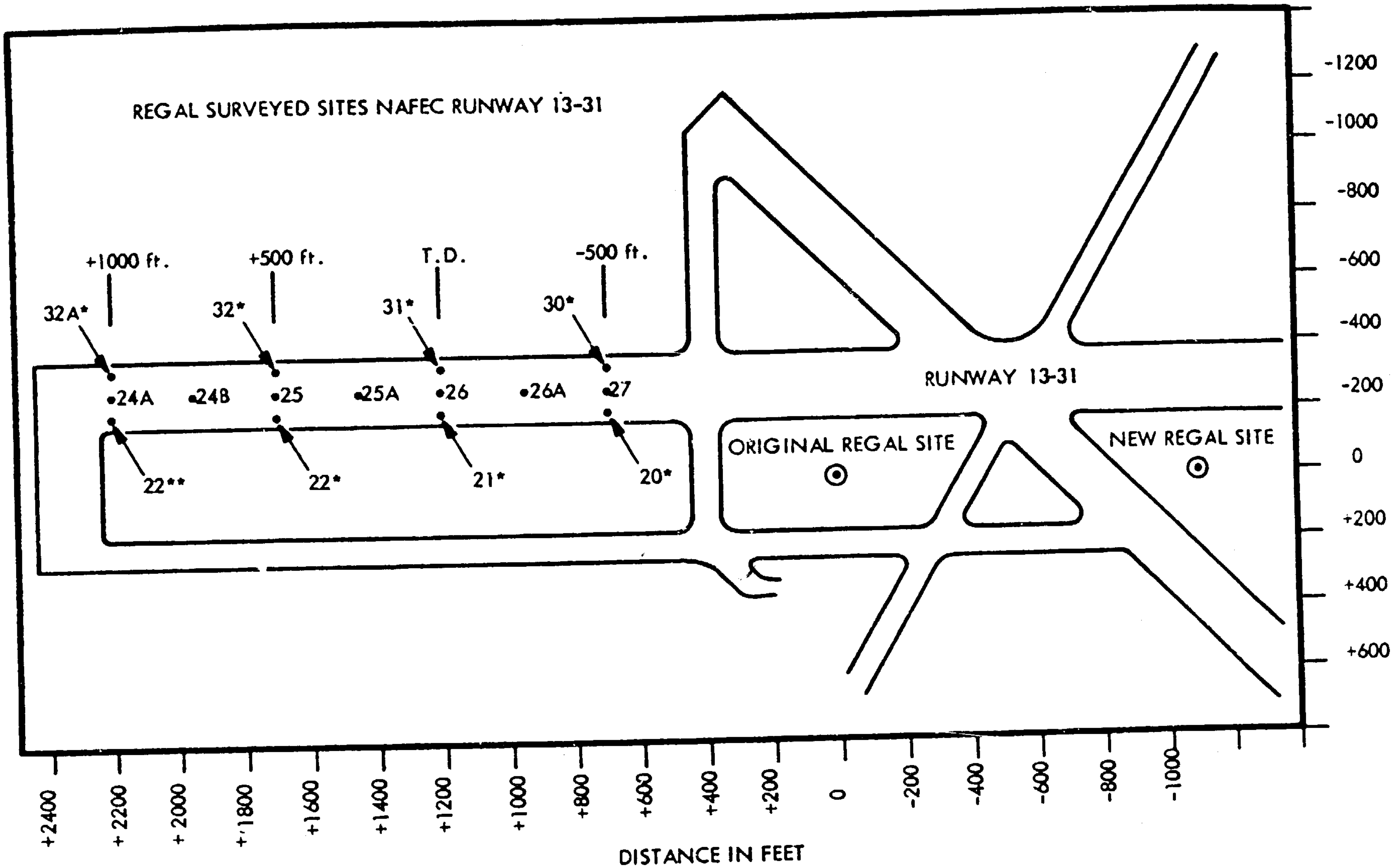


Figure 3-1b. NAFEC Regal Installation Survey

Before performing the static tests using the mobile test truck, a complete second order survey was performed and approximately 30 bench marks were installed in the touchdown zone. Several rechecks of the surveyed positions were necessary to eliminate original survey errors. In some cases, the location of the bench marks did not allow easy accessibility; consequently, it became necessary to relocate some of these to more desirable locations. See Appendix A for tabulation of the site survey data.

3.1.1.1 Ground Equipment Enclosure. - The shelter enclosure was designed to optimize the radiation coverage of the REGAL transmitting antenna. A large radome window of fiberglass honeycomb construction was installed directly in front of the antenna arrays as shown in Figure 3-2. This not only provided the necessary protection against weather, but also allowed for easy installation of the antenna scanner. The building was of wood frame construction on a concrete foundation. The ground transmitting equipment was installed immediately adjacent to the antenna scanner. To facilitate the testing program, both telephone and radio communications were provided. The only equipment not completely enclosed by the facility was the delay line cable reel which was located at the rear of the building and was protected by a temporary enclosure.

3.1.1.2 Equipment Collimation and Leveling. - The shipment of the equipment to NAFEC from the Gilfillan test facility in California required removal of the antenna arrays from the scanner. A thorough leveling and collimation of the antenna system was performed to insure the following:

a. The effective antenna scan axis must be horizontal within 0.05 degrees to maintain the data accuracy for the azimuth coverage zone.
b. The components of the antenna scan drive mechanism must be aligned to obtain vibration-free operation.
c. The relative alignment of the two antenna arrays and the associated data take-offs must be within 0.02 degrees to minimize the alternate scan noise.

Gilfillan Engineering personnel conducted the initial alignment because the experimental system did not include operational type alignment facilities.

The leveling of the mount was accomplished using a precision level and several simple support brackets. The procedure included five basic steps as follows:

a. Leveling of the frame on the concrete footing.
b. Alignment of the trunnion axis supports to insure that the two axes were in line and that the antenna arrays were vertical.
c. Alignment of the fly wheel shaft axis to insure that the antenna, push rod and crank motion were in one plane.

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RADOME
WINDOW

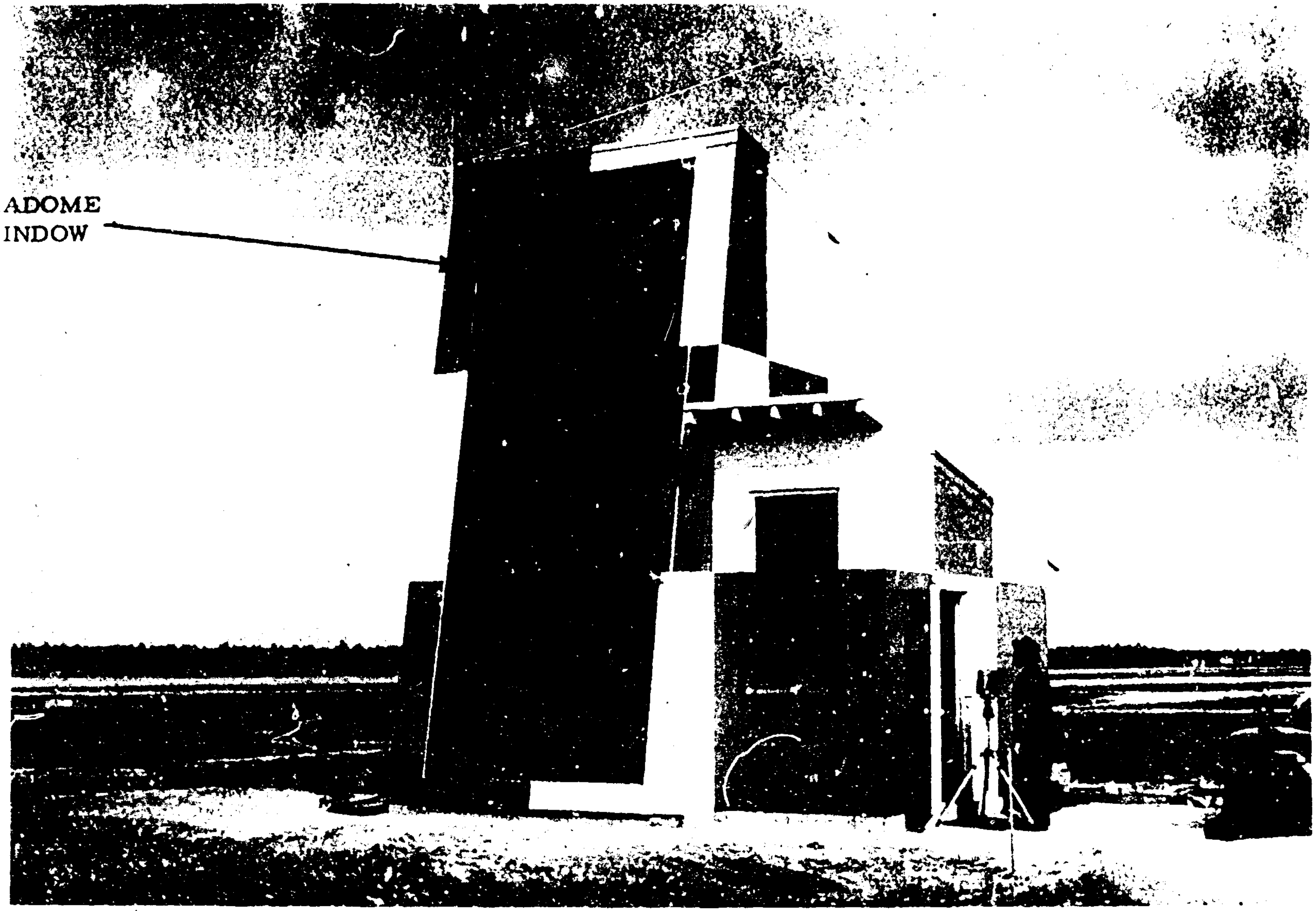

Figure 3-2. NAFEC REGAL Ground Facility

d. Set up of the optical data take-off units for the correct alignment and minimum unit scan noise.
e. Verification of the system alignment using the mobile test vehicle.

When completed, the leveling was within the required accuracy in both axes with the scan axis of the antenna 9-1/2 feet above the concrete foundation.

3.1.1.3 Second REGAL Ground Equipment Site. - Later in the REGAL test program it was decided to perform comparison tests between REGAL and Flarescan. These tests primarily concerned the ability of these systems to provide airborne derived data capable of guiding aircrafts on curvillinear flare paths to touchdown. Two aircrafts equipped for both of the systems were used for these tests. These were the FAA owned C-54 (BRAD 12) and the Bendix B-25 aircrafts. It was desired that initial glidepath used by both systems be provided by either the NAFEC ILS systems or REGAL. Since a flare path executed from this glidepath would result in touchdown approximately 600 feet from the original REGAL site, a very limited zone for touchdown dispersion remained. Consequently it was decided to relocate the REGAL ground tramsmitting facility to approximately 1100 feet behind the original site (See Figure 3-1b). A new concrete foundation was installed and the complete REGAL system including the protective shelter was moved in October 1962.

3.1.2 Mobile Test Vehicle. - Retrofitting of a government surplus ordnance repair truck was done by NAFEC personnel to accommodate the static testing of REGAL receivers. As shown in Figure 3-3, an aluminum test mast with a REGAL antenna, which could be positioned vertically on the mast, was installed in order to make static measurements in altitude. The REGAL antenna height was manually adjustable to any height from 2 to 40 feet above the vehicle roadbed. The rear compartment of the truck was provided with a complete test and alignment bench facility and an instrumentation bench as shown in Figures 3-4 and 3-5. Electrical power was provided by a 1500 watt gasoline motor generator when mobile, and commericial power when located at the truck's "home" site. This primary power was converted to 400 cycle and direct current voltages by means of alternators and motor generators. The instrumentation provided was a six channel brush recorder, a ten channel digital printer, and a precision null voltage test set. The brush recorder was primarily used to judge the quality of the REGAL data being gathered. The precise angular data from REGAL was permanently recorded by means of the digital printer. Although primary emphasis was not given to static range measurements, the use of the null voltage test set provided a means of manually recording its readings.

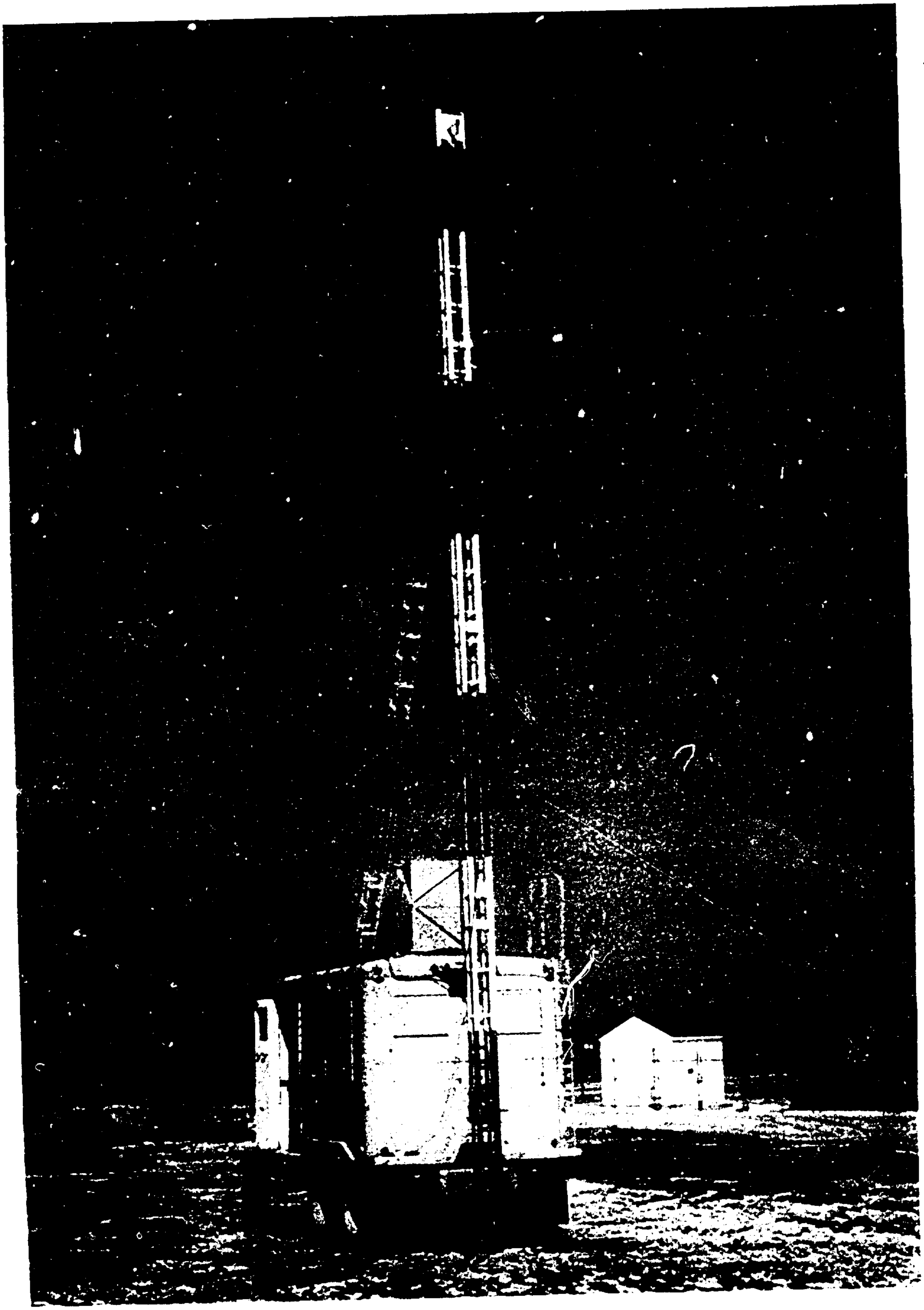

Figure 3-3. Mobile Test Vehicle

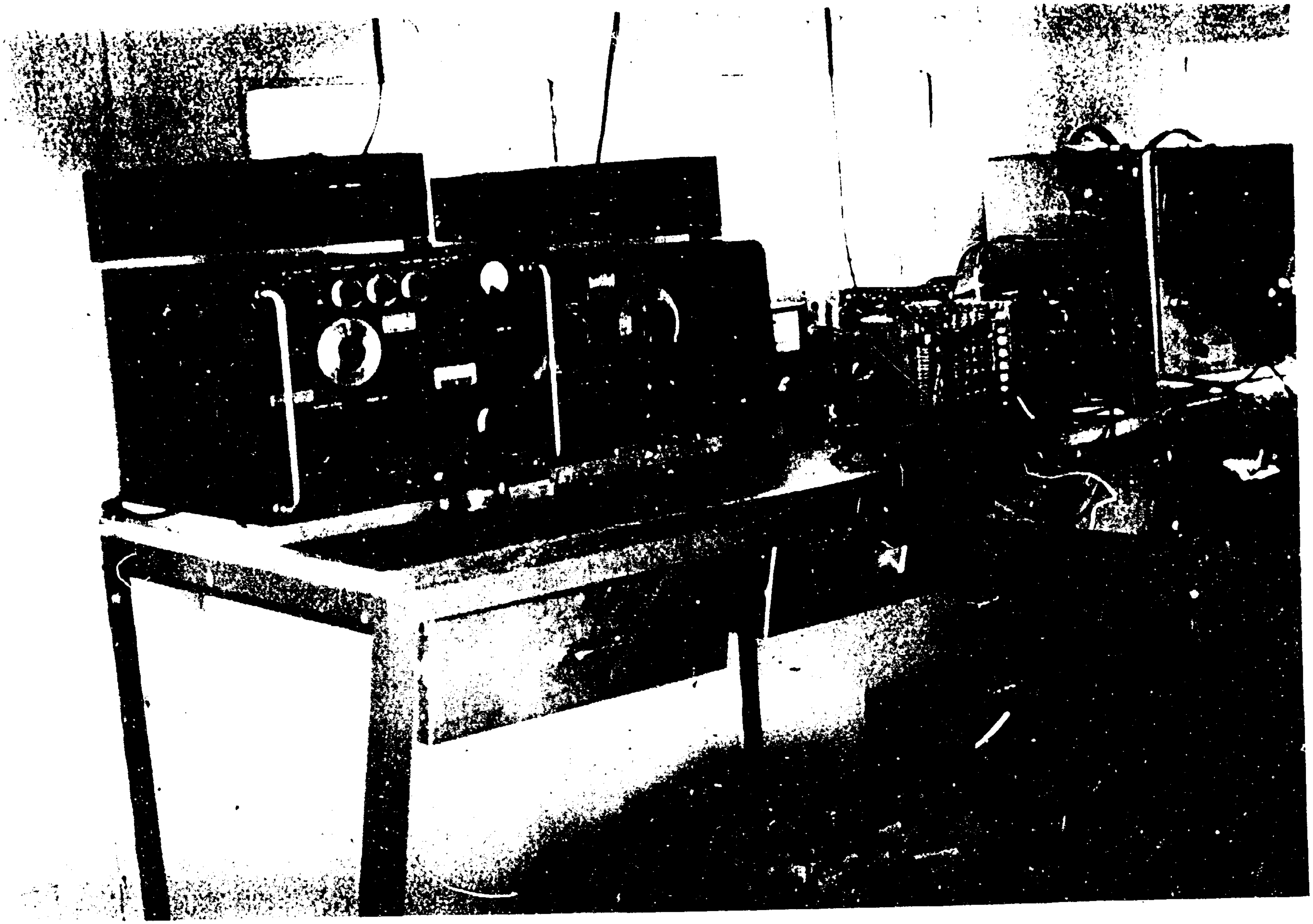

Figure 3-4. Test and Alignment Bench

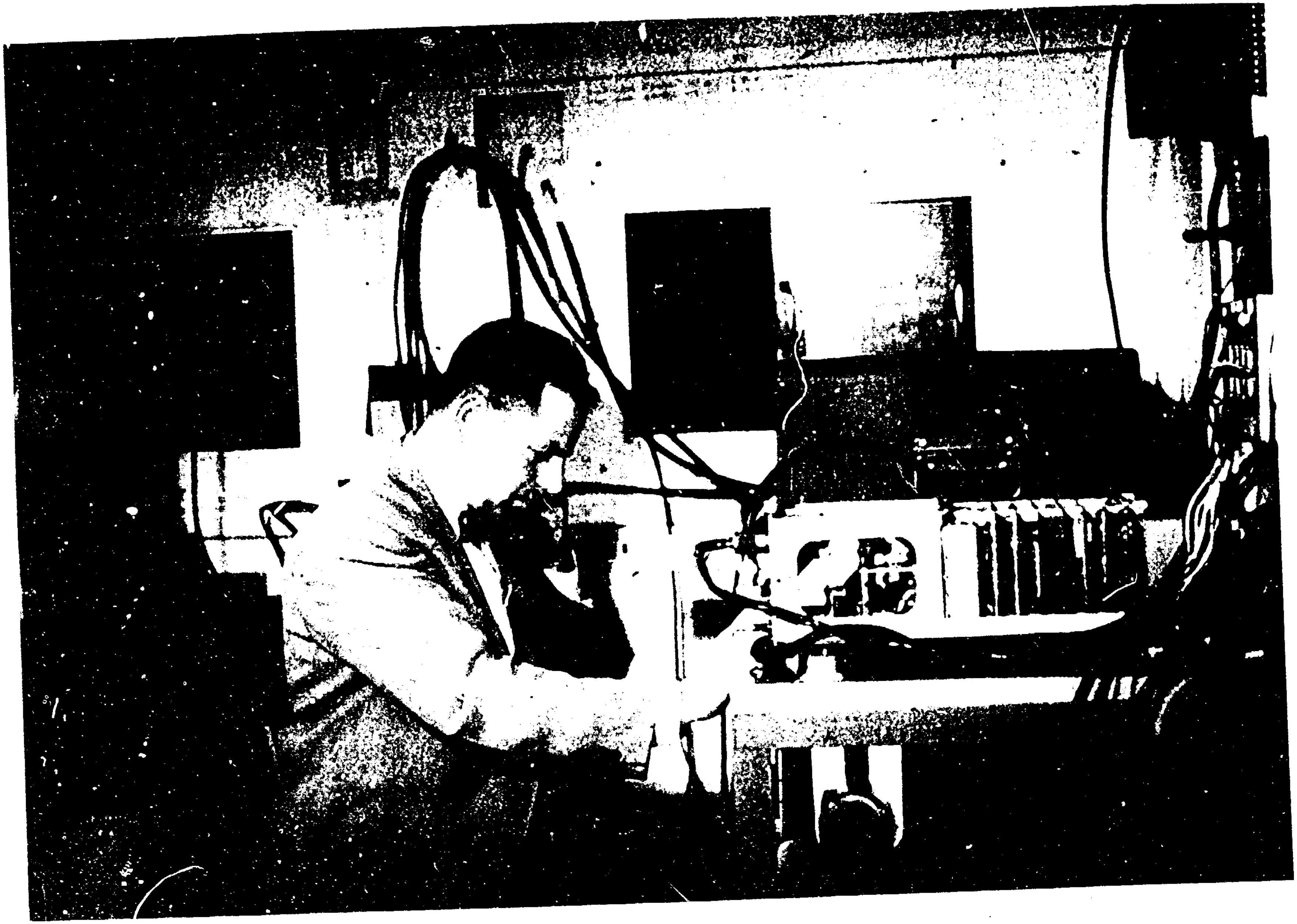

Figure 3-5. Instrumentation Bench

3.1.3 C54 Aircraft Installation. - The primary test bed aircraft used on the REGAL program was the NAFEC C54 (BRAD12). This aircraft was not only used for the landing system evaluation portion of the program, but also to gather the dynamic data on the REGAL system. The reason this aircraft was chosen for this purpose was because of its capability of carrying the large weights involved with the necessary instrumentation equipment.

3.1.3.1 Original C54 Installation. - The REGAL observers position was located in the forward starboard section of the cargo compartment. This position was chosen for installation of the REGAL receiver and coordinate converter with its associated test apparatus. The antenna was mounted in the radome as shown in Figure 3-6, and connected to the REGAL receiver with approximately 40 feet of X-band waveguide. Although this would not necessarily be the length of waveguide used in an actual installation, it did allow easy maintenance when it became necessary. An aluminum shelf was fabricated and permanently mounted to the cabin outer wall (see Figure 3-7). This shelf provided a suitable mounting not only for the REGAL receiver but also several pieces of test apparatus needed by the observer for monitoring REGAL data quality. Immediately above this shelf on the cabin outer wall, a special group of monitoring equipment was installed. This equipment provided the observer with a digital readout of the REGAL angle data and various indicators needed to measure the quality of AGC, Range, and Elevation Analog Voltages. Immediately below the REGAL receiver shelf and to the left against the Cabin (cockpit) wall was located the Coordinate Converter unit. This unit was needed to convert the REGAL elevation and range analog signals into acceptable signals needed by the Sperry Landing System. The portable racks, shown in Figure 3-8, containing digital printer and six channel brush recorder were installed in the starborad side of the mid-section cargo compartment. This equipment was provided for the purpose of quick analysis of the signals being received to determine in advance, problem areas concerning reduction of data recorded by the primary instrumentation equipment. This installation provided a means of recording REGAL received data without elaborate instrumentation being used when survey flights were performed.

3.1.3.2 Improved C54 Installation. - During the first phases of the test program, the C54 aircraft was assigned to other programs which required removal and replacement of the REGAL equipment. For this reason and because of various interference problems experienced in the aircraft wiring, it was decided in July 1962 to group all the REGAL equipment and associated monitoring equipment in one location. This along with relatively quick disconnect devices eased the removal and replacement problem. The new equipment racks which were located in the front starboard side of the cargo compartment are shown in Figure 3-9. The aircraft instrumentation also was improved with newer equipment at

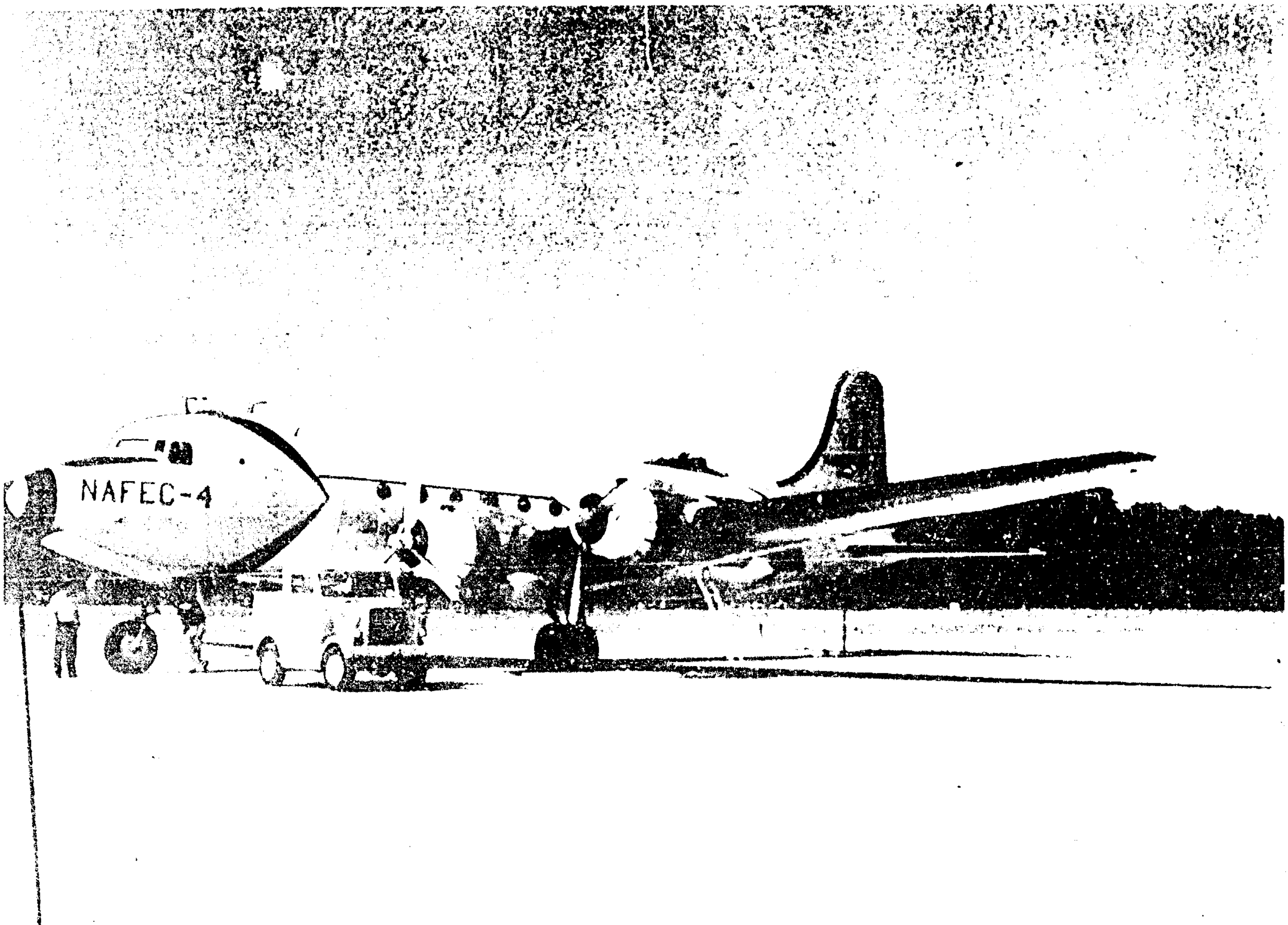

Figure 3-6. C54 Aircraft

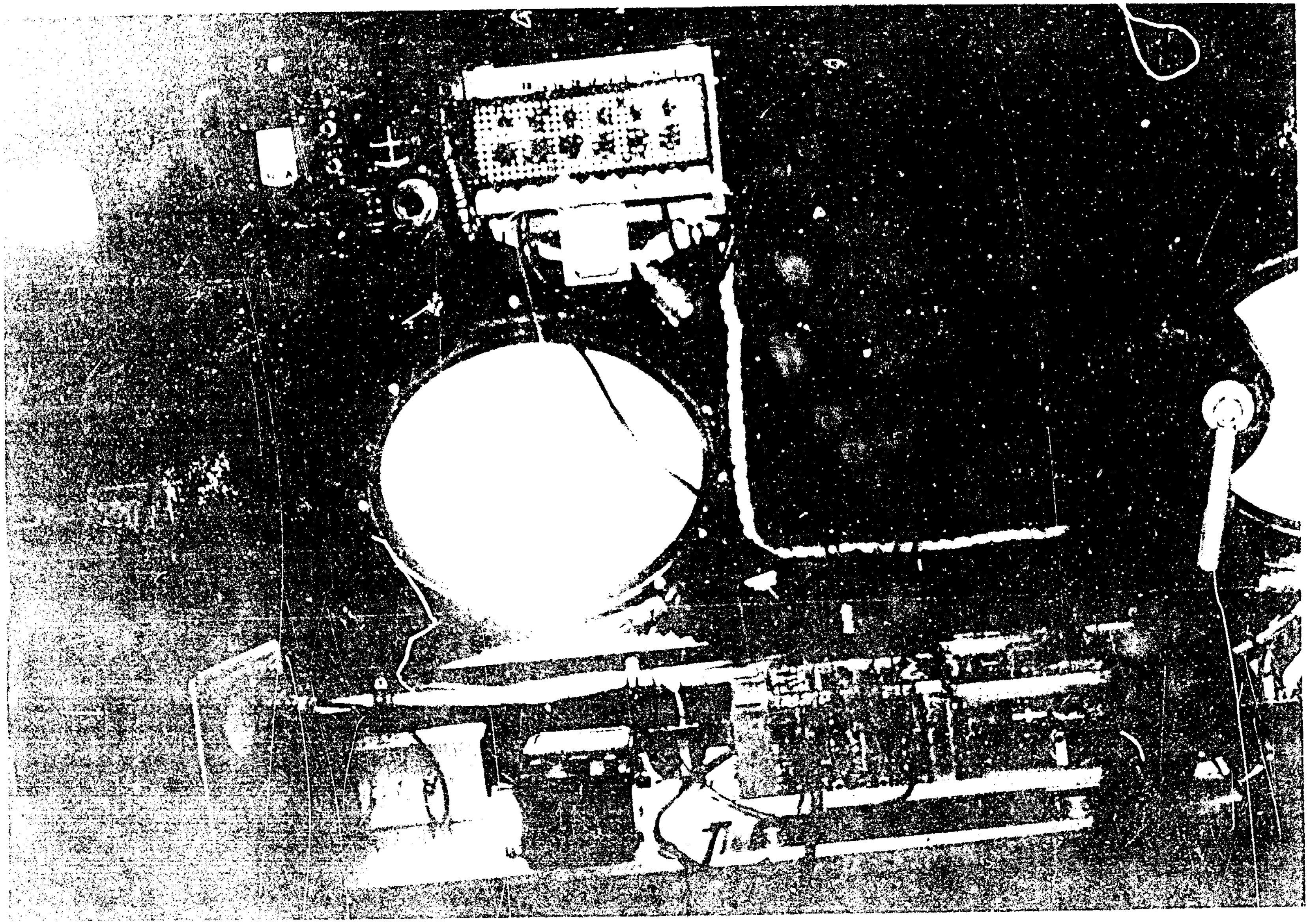

Figure 3-7. REGAL Observers Position in C54 Aircraft

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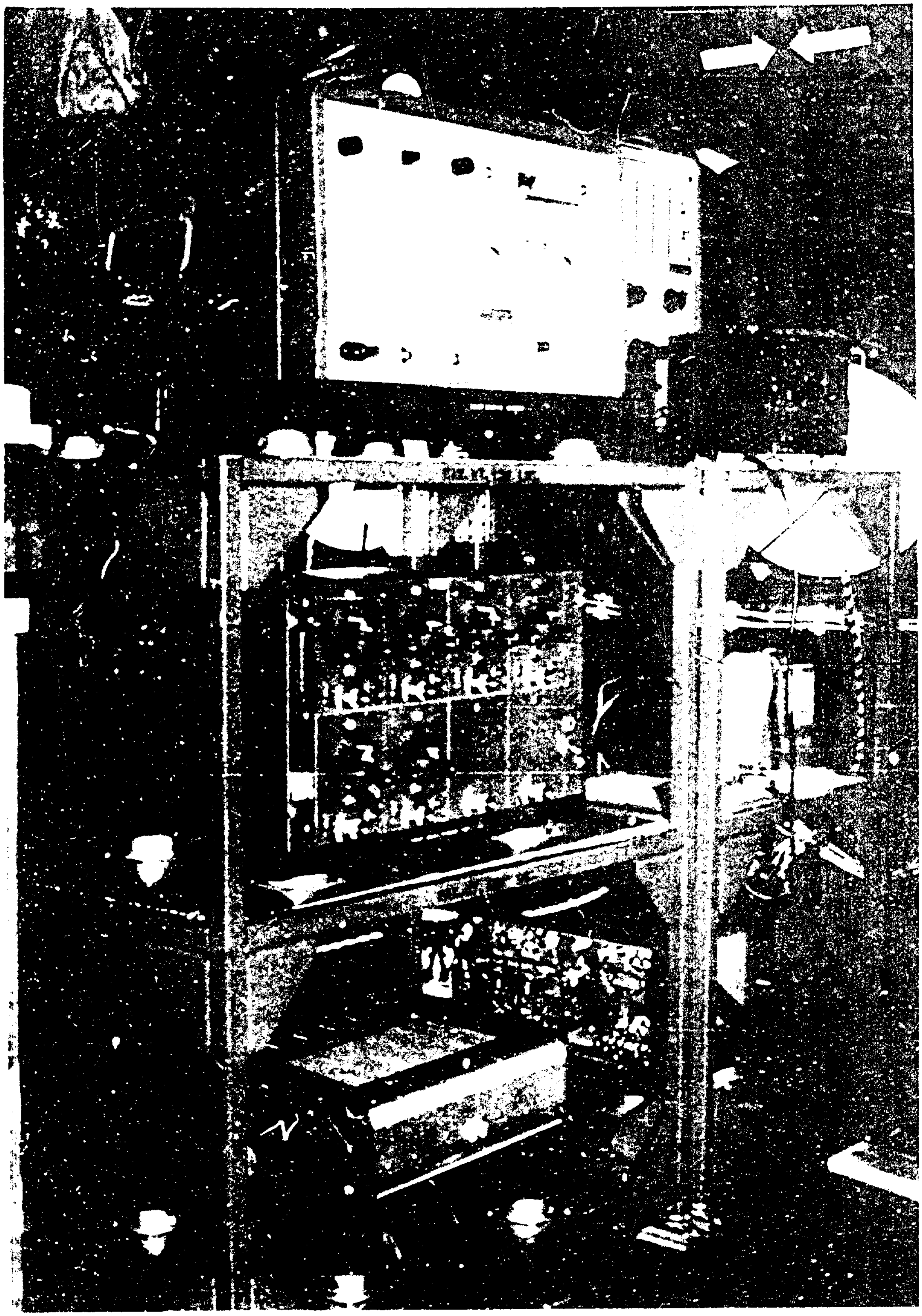


Figure 3-8. REGAL Monitor Recording Position in C54 Aircraft

Figure 3-9. Improved REGAL Installation in C54 Aircraft

this time, but the basic facility remained in the same place.

3.1.3.3 C54 Cockpit Instrument Installation. - The only additional instrument installed for the benefit of REGAL was a range meter as shown in Figure 3-10. This instrument provided the pilot with data concerning range to REGAL on either one of two scales. A switch directly below the indicator allowed for selection of a 10 mile or 2 mile scale. The REGAL glide slope data from the coordinate converter was used to drive the existing panel indicators; an ID 249 located in front of the Co-Pilot and the Collins Flight Director Indicator in front of the pilot. Appropriate switches were installed in the radio compartment which allowed change-over from using normal ILS glide slope signals to REGAL at the pilot's discretion.

3.1.3.4 Instrumentation Equipment. - The necessary recording apparatus for collection of data for REGAL was located in the cargo compartment on the forward port side. The basic equipment was a 32 channel Minneapolis Honeywell galvanometer recorder. Along with recording the outputs of the REGAL receiver and coordinate converter, the various signals concerning the flight control and landing system were also recorded. To correlate this recording with the photo-theodolite data being gathered on the ground, a communications link provided synchronization signals to the recorder's timing channel. This recorder had the ability to provide a "quick look" at the gathered data shortly after each flight; but due to the bulkiness and sensitivity of the paper, this did not prove feasible. Consequently, the recorded data remained intact in roll form until the final flight for the day was finished.

3.1.3.5 Landing Computer. - This unit was designed and built by Sperry Gyroscope Company of Great Neck, New York. Figure 3-11 is a general block diagram of the combined system which shows the principal signal paths along the various elements. Basically the functions of the flareout computer are to generate the appropriate approach paths and flare trajectories which are compared with the REGAL measured data to generate path error signals and to sequence the different operations during the approach and flareout. A throttle control system is also provided to maintain the appropriate airspeed during the approach and flare trajectories.

The control signal used for the approach phase is the angular flight path error ($^{\Delta}r$) from the REGAL coordinate converter is provided by a control unit supplied to the pilot. Scaling of this error before being applied to the autopilot is provided by the flareout computer. Auxillary units within the computer provide necessary course softening of the error as a function of range. The altitude and rate of decent sections of the computer do not play an active part in aircraft control during the initial approach phase. During this time they are allowed to become synchronized with the data derived from the REGAL coordinate converter. The vertical rate section is synchronized to the REGAL range rate term multiplied by the selected approach angle. The altitude section becomes synchronized to the REGAL fine altitude after the aircraft reaches

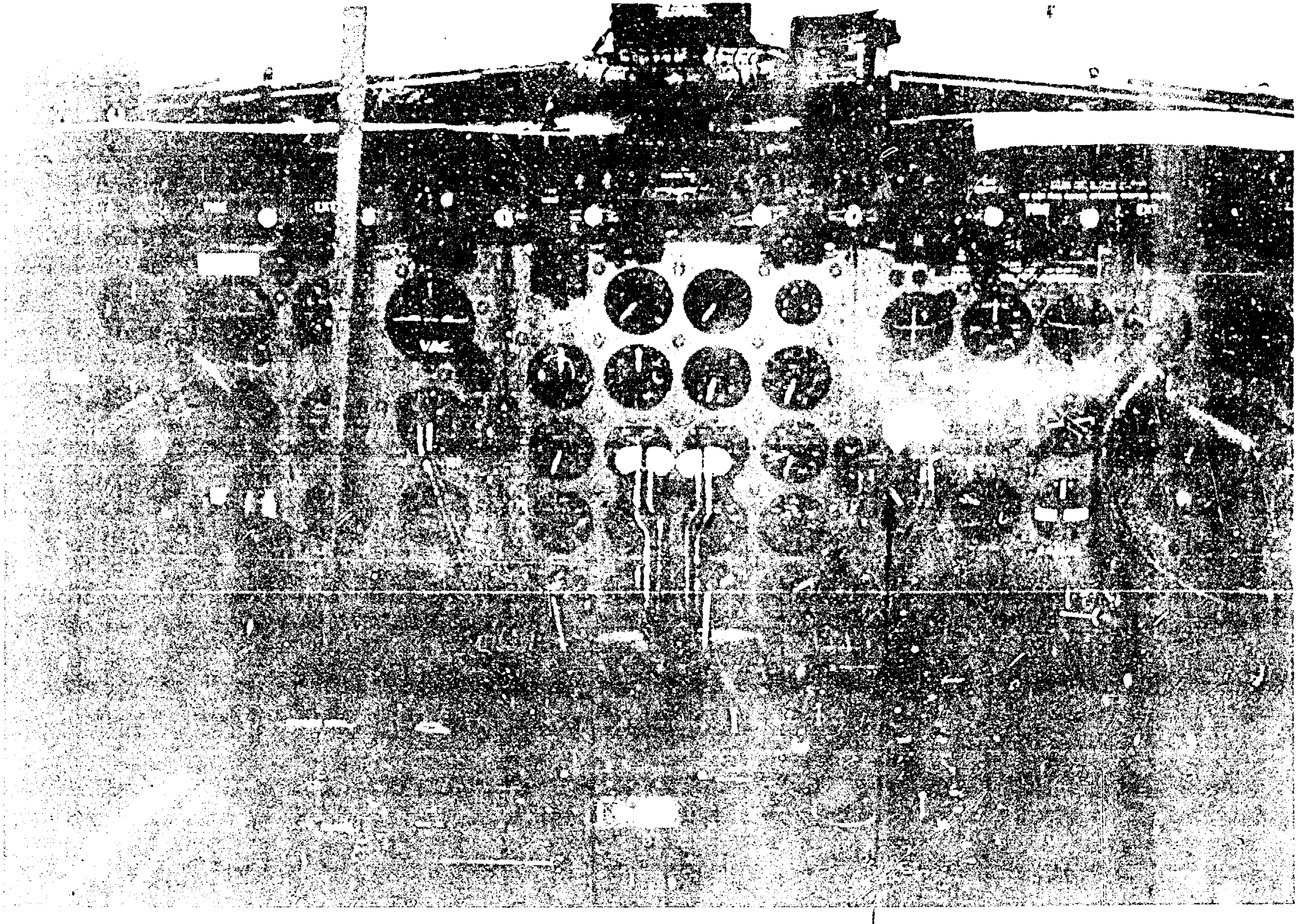


Figure 3-10. C54 Cockpit Range Meter

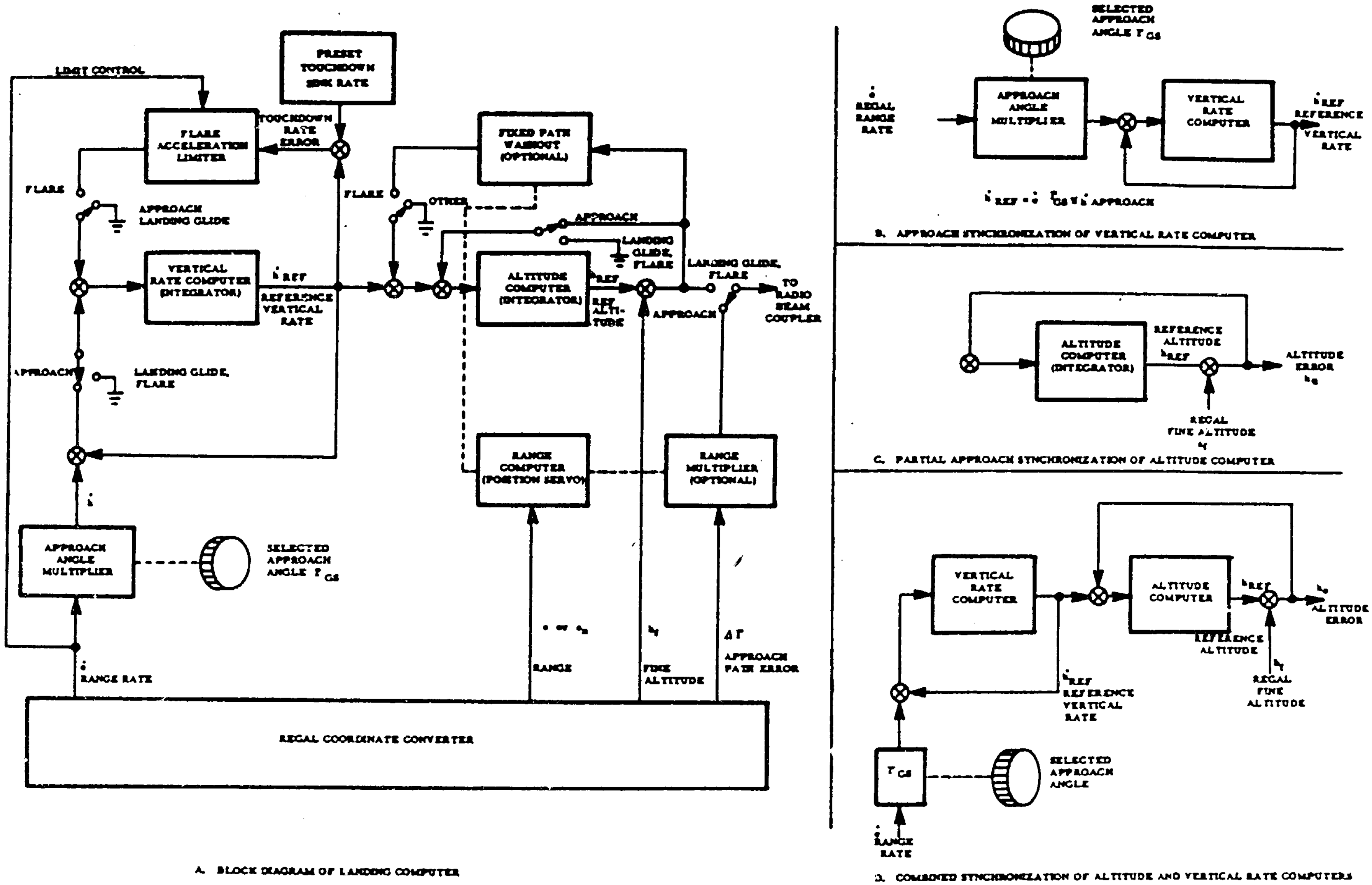


Figure 3-11. Landing Computer - Block Diagram

250 feet altitude. The synchronization provides for a smooth transition to the final approach and flareout phase. This generally occurs at approximately 200 feet altitude for normal approach angles. When this point is reached, the synchronized altitude replaces the angular approach path error. Throughout the remainder of the final approach and flareout phase, the error signal corresponds to the differences between REGAL measured altitude and the desired altitude generated in the altitude and rate of decent portions of the computer. During the flare maneuver, the desired rate of descent is reduced from the value memorized during the approach phase to a value suitable for touchdown. This reduction of rate of descent is accomplished by integrating the memorized value downward towards a terminal value of approximately 2 feet per second. Since the rate of change of the vertical rate reference corresponds to vertical acceleration, the net effect is to provide a constant flare acceleration. Corrections in the flare acceleration are made as a function of REGAL measured ground speed to compensate for variations in approach speed. The trajectory is therefore adjusted to maintain a 0.04 G nominal acceleration. When the final sink rate portion of the flare has been reached, this value is then maintained until the aircraft reaches touchdown.

Throughout the landing phase, lateral position of the aircraft is provided by the FAA's new improved localizer. In the landing phase the wings are held essentially level and lateral control is maintained by skidding. This arrangement permits tight control of the localizer track without requiring excessive roll angles near the ground. Prior to touchdown, any crab angle is removed by skidding the aircraft to align it with the runway heading present on the pilot's course indicator. A combination of runway heading and localizer deviation signals provides rudder control during the early stages of ground roll.

3.1.4 Aerocommander Aircraft Installation. - Prior to the NAFEC test program, the FAA Aerocommander aircraft (BRAD 22) was equipped with the antenna, REGAL receiver and the necessary wiring by Lear Inc. of Santa Monica, California. A flarepath computer built by Sierra Research Corp., Buffalo, New York was also installed. It was planned that this aircraft would be utilized in the test program at NAFEC, primarily for analysis of the flight control capabilities of the Lear Sierra Computer-Autopilot combination.

3.1.4.1 REGAL Receiver Installation. - Installation of the REGAL reveiver was designed to minimize the congestion within the cabin, hence it was located in the rear baggage compartment. This installation, as shown in Figure 3-12, presented the problem of a longer waveguide run, but was easily accomplished

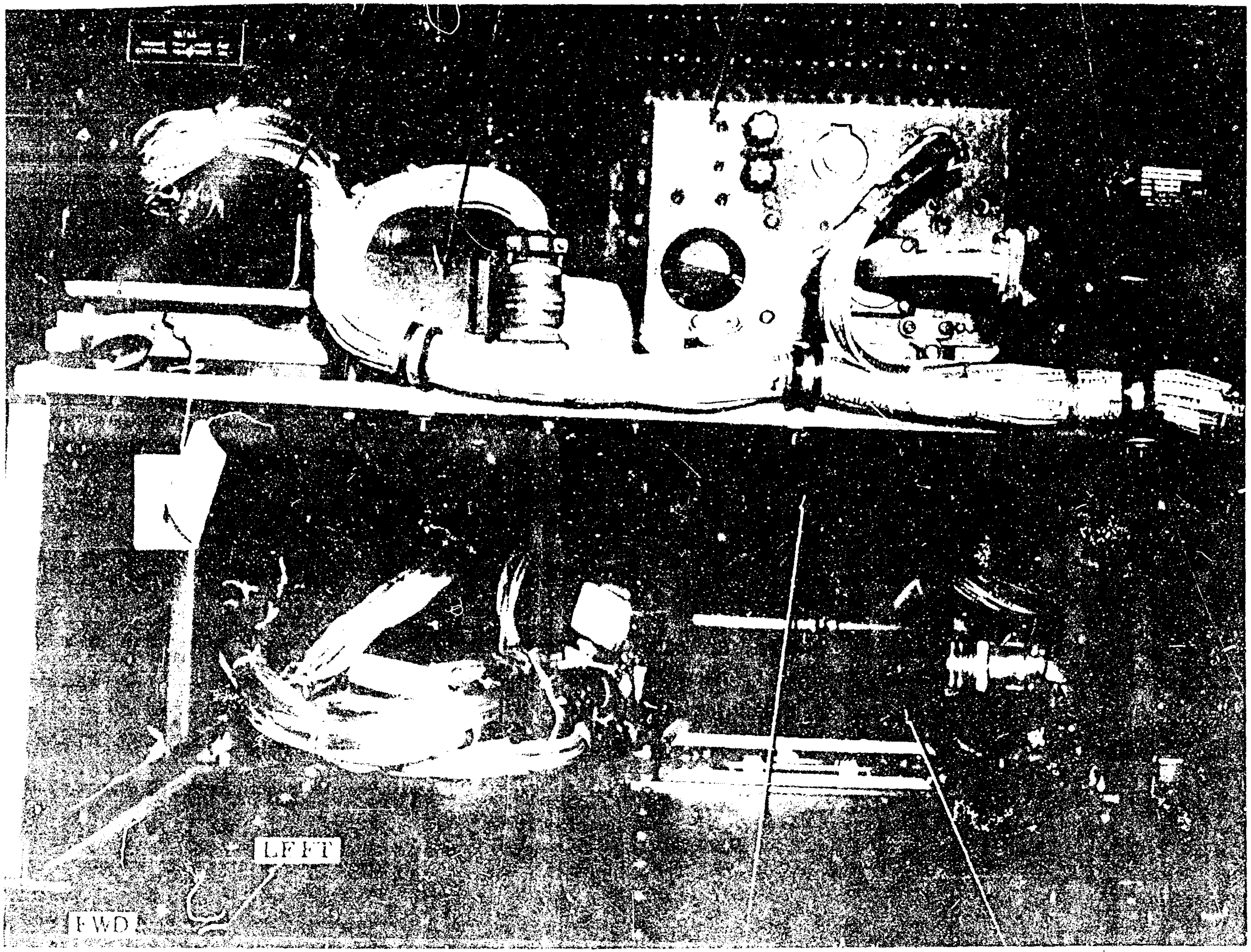


Figure 3-12. REGAL Receiver Mounted in Baggage Compartment of BRAD-22

by running most of it outside of the cabin. The REGAL antenna was mounted above and to the rear of the pilot's head (see Figure 3-13). An X-band waveguide run was installed along the top of the fuselage, from the REGAL antenna to a point 10 feet aft of where it was passed through the aircraft skin. From this point, it was routed 40 inches down and into the baggage compartment, ending in a flexible waveguide capable of being connected to the REGAL receiver. As shown, the external waveguide and antenna were covered with sheet metal fairings to minimize aerodynamic drag.

3.1.4.2 Monitor Equipment. - The monitor equipment was held to a minimum because of the limited amount of space available within this aircraft. The angle data light panel was located just above the pilot's windscreen. This display consisted of 10 lights, each indicative of one of the 10 binary angle flag conditions. On the co-pilot's side, a mounting facility was provided to hold a dual meter assembly which could indicate the REGAL d.c. analog outputs for range, angle, and AGC. This monitor meter could be removed and held in the co-pilot's lap if desired.

3.1.4.3 Instrumentation Equipment. - After the equipment arrived at NAFEC, personnel of the Airborne Data Gathering Branch installed a 32-channel Minneapolis Honeywell galvanometer visacorder for the purpose of recording REGAL, Sierra Flight Path Computer, and Lear auto-pilot data. To facilitate the synchronization of the recorder to the ground theodolite stations, a receiver capable of receiving the NAFEC timing signals was provided and its output was recorded on the visacorder. A specially fabricated patch panel provided for connection of various parameters to the recorder in addition to a means of injecting standard calibration signals before and after flights.

3.1.4.4 Aerocommander Cockpit Installation. - The new Instrument panel which was fabricated by Lear Inc. prior to the REGAL test program is shown in Figures 3-14 and 3-15. The instruments used are of standard type with the exception of the "Altitude-Distance" readout unit. This instrument provides the pilot with air-derived REGAL altitude and range display of a digital type. Also located in this panel is an indicator for displaying the climb rate derived from REGAL and a group of illuminated enunciators describing the status of the airborne computer.

3.1.4.5 Landing Computer. - The airborne computer was designed and fabricated by Sierra Research Corporation. Its function is to accept inputs from the REGAL system, pilots inputs (desired glide angle, flare path) and to compute error signals to be supplied a modified Lear L5 autopilot.

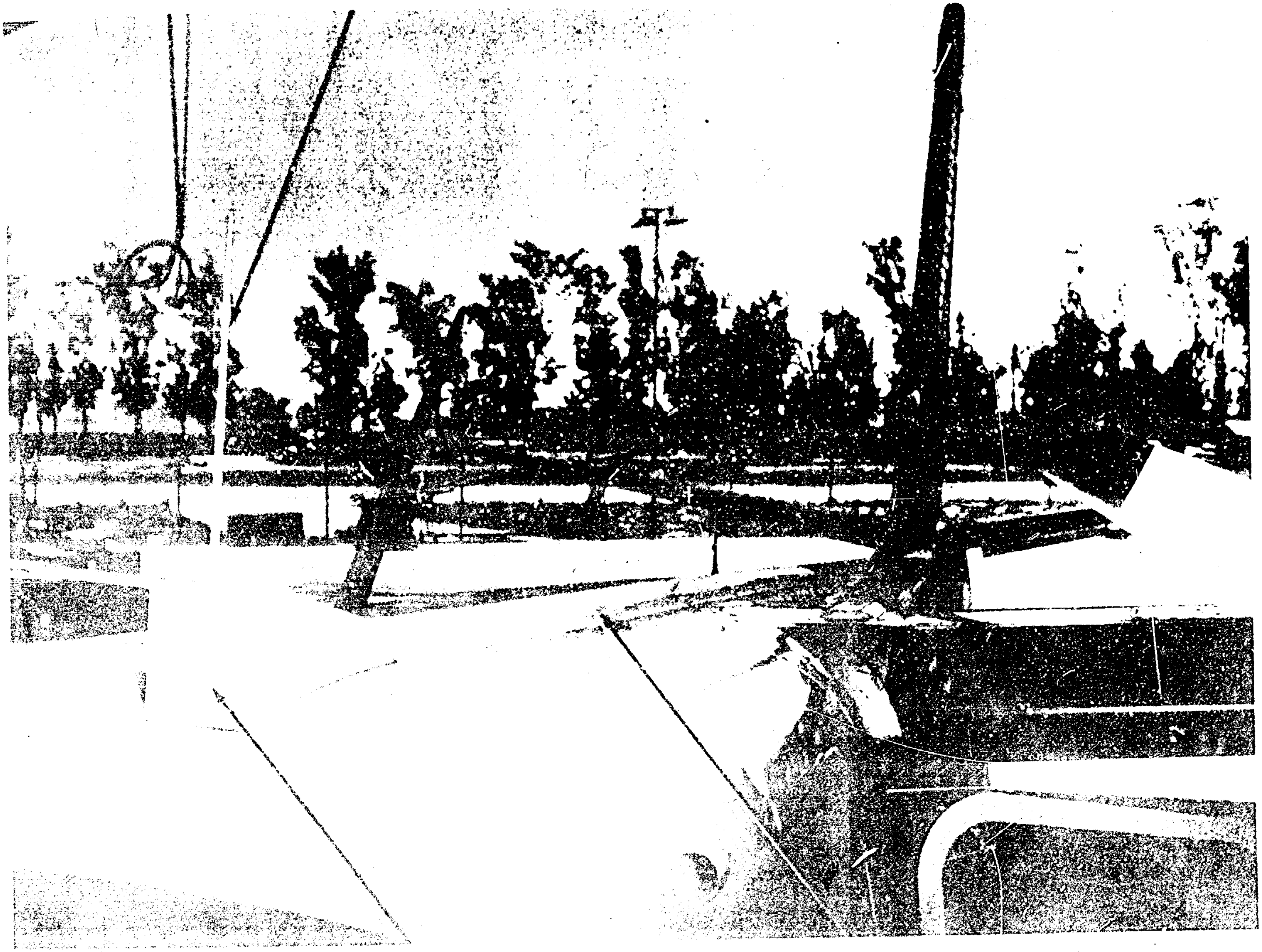
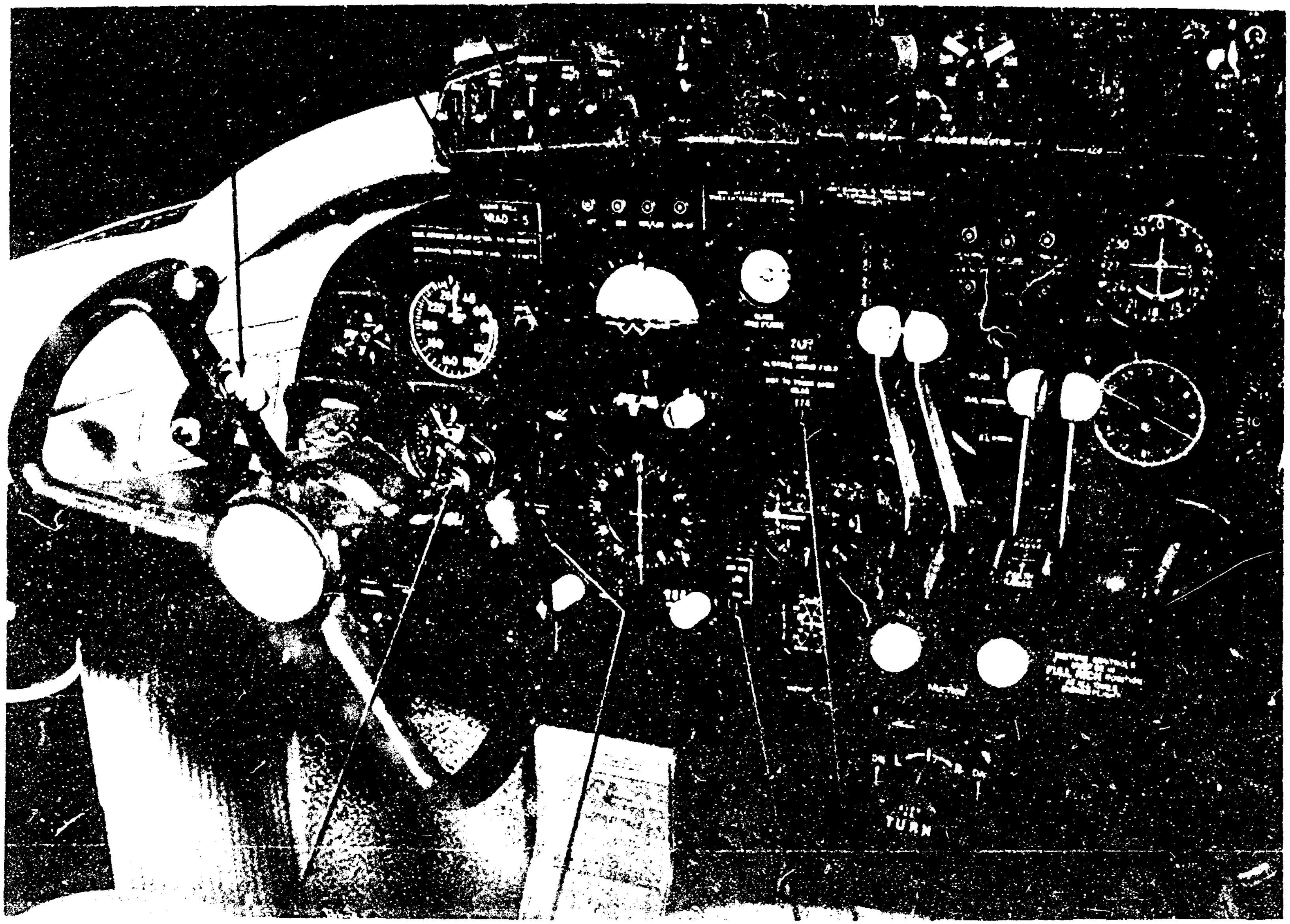


Figure 3-13. REGAL Antenna Installation On BRAD-22

A/P REL SWITCH HSI ADI HSI MODE SEL A/P TRIM INDICATOR A/P MODE SEL



PITCH BEEP SWITCH REGAL-ILS TRANS SWITCH ST ADI DIM SWITCH A/P FLIGHT CONTROLLER ALT-DIST READOUT

Figure 3-14. Modified Pilot's Instrument Panel, BRAD-22

A/P REL. SWITCH

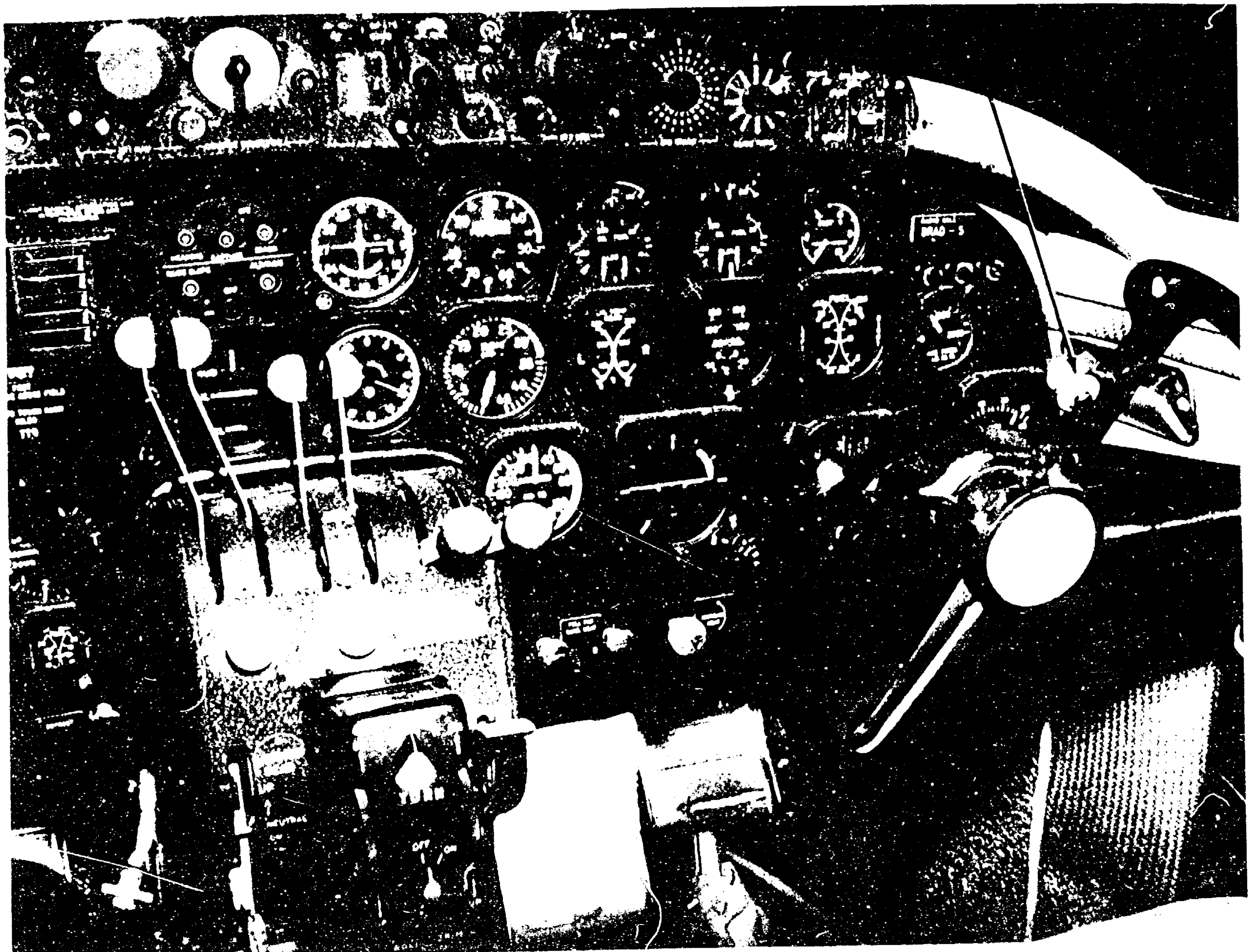


Figure 3-15. Modified Co-Pilot's Instrument Panel, BRAD-22

A simplified block diagram of the computer is shown in Figure 3-16. REGAL range and elevation angles enter the computer as d c analog signals. The Range to touchdown, Xp, and the range rate $\dot{x}$ are computed in an instrument Servo (shown at top of Figure 3-16) by subtracting a touchdown offset constant, a, from REGAL Range. A tach generator on the instrument servo provides a voltage, x, proportional to range rate.

The Aircraft Altitude is computed by multiplying Regal Elevation Angle, θR, by Range to touchdown, Xp. Connection factors for the touchdown offset, a, and the antenna height, h_o, are also added. This signal is used to position another instrument servo whose shaft position represents altitude. A tach generator furnishes an altitude rate signal.

During the glide phase, the desired altitude signal is generated by first subtracting from Xp a voltage, X_a, proportional to the offset between glide aiming point and the touchdown point and multiplying the difference by the selected glide angle, θG. The desired altitude rate, $\dot{h}_D$, is generated by multiplying $\dot{X}$ by the selected glide angle, θG. The desired values of h_D and $\dot{h}_D$ are compared with h and $\dot{h}$ and the resulting error scaled as a function of range and supplied to the autopilot pitch axis.

During the flareout, the error signal is generated by multiplying X by h and feeding this into a division circuit consisting of a high-gain d c amplifier with a potentionmeter in the feedback positioned by X_p. The resultant signal is proportional to $\frac{2\dot{X}h}{Xp}$ which forms a parabolic flarepath. For a cubic flarepath, the signal is multiplied by 1.5 giving $\frac{3Xh}{Xp}$. To this signal is added the bias signal representing the desired touchdown sink rate $\dot{h}_T$. The signal, $\dot{h}_D$, is now compared with $\dot{h}$, and the resulting error signal is switched into the autopilot upon flare engagement.

Since the cubic and parabolic flare paths have a slope which is greater at longer ranges, the $\dot{h}_D$ term computed by the flare path computer is much greater than h during glide. At one point, the two signals are equal, representing the point at which the glide slope is tangent to the flare path. A comparator circuit switches the autopilot from glide to flare at this point.

3.1.5 B-25 Aircraft Instrumentation. - A B-25 aircraft owned by Eclipse Pioneer Divsion of the Bendix Corporation was used in the REGAL test program initially in conjunction with a USAF study contract. In 1962 and 1963 the aircraft was used for a FAA contract to study the comparative performance of the REGAL and Flarescan landing systems. Support data of this aircraft including installation of REGAL components was provided by Bendix.

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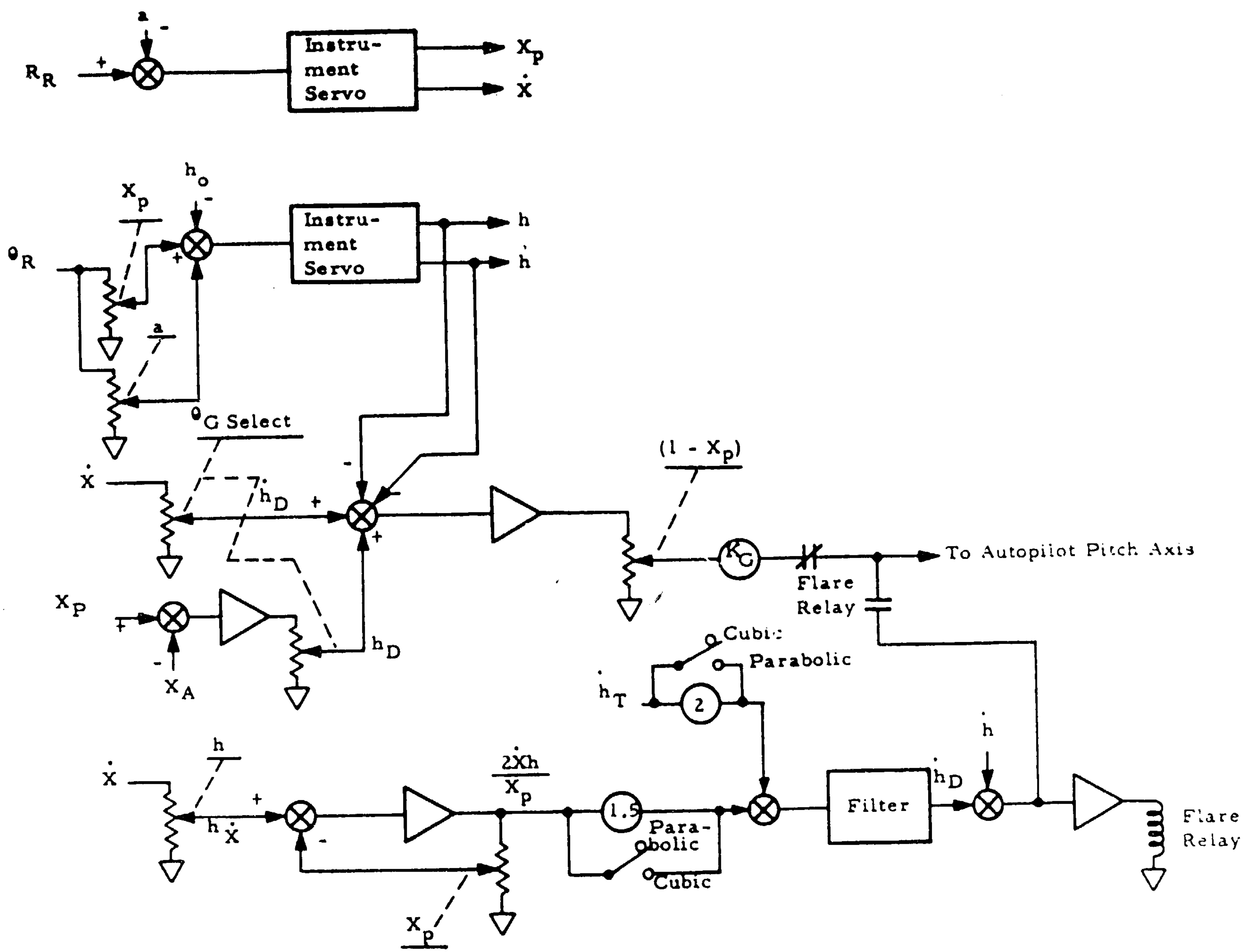

Figure 3-16. Sierra Computer-Simplified Block Diagram

3.1.5.1 <u>REGAL Receiver Installation.</u> - The original installation of the receiver provided for an extremely short waveguide run from the antenna. The antenna was located on the nose of the aircraft as shown in Figure 3-17 approximately nine feet above the wheels. The REGAL receiver was located in the forward gunner's compartment. During the early stages of the test program, it was noted that this compartment did not provide a suitable environment for the receiver on extremely hot days. Consequently, the receiver was moved to the bomb bay compartment. This improved the overheating conditions considerably, but resulted in limited access to perform checks on receiver during flight.

3.1.5.3 <u>Monitor Equipment.</u> - The basic outputs of REGAL (i.e., elevation angle and range) were monitored by conventional voltmeters mounted in the upper center of the pilot's windscreen so that all of the crew could observe the indications. The meters for range and angle were provided with calibrations and scale factors to accommodate 0 to 10 miles and 0 to 10 degrees respectively. The glidepath error and flag information for REGAL was displayed on an ID249 indicator, mounted directly in front of the pilot.

3.1.5.2 <u>Landing Computer.</u> - Several versions of landing computers have been used in the B-25 aircraft during the different flight test phases. The latest configuration used during the fall of 1962 and 1963 is described here as the most advanced version. This computer has the following features.

a. The ILS glidepath is used for initial approach.
b. REGAL information is used for glidepath extension.
c. An accelerometer is used for augmenting vertical rate information.
d. The computer can alternately operate from a radio altimeter.

A block diagram of the REGAL landing computer as implemented on the B-25 is shown in Figure 3-18. A brief functional description of each of its major subsystems is given in this section. The ground equipment and airborne REGAL receiver were furnished by the FAA to Bendix. The output quantities used from the REGAL receiver were the d-c signals proportional to range from the transmitter, and elevation angle. These are converted to altitude and augmented altitude rate signals in the Data Processing Unit.

The computer has three modes of operation as follows:

a. Glidepath capture mode using the normal PB-20 ILS glidepath coupler. During this mode the flare coupler is synchronized to the rate of descent derived from REGAL.
b. The Track mode using ILS path error from integral control together with "washed out" altitude rate data for displacement control.
c. The flareout mode using REGAL altitude and altitude rate to compute an exponential flareout path. The flare is begun at a pre-selected altitude of 45 feet.

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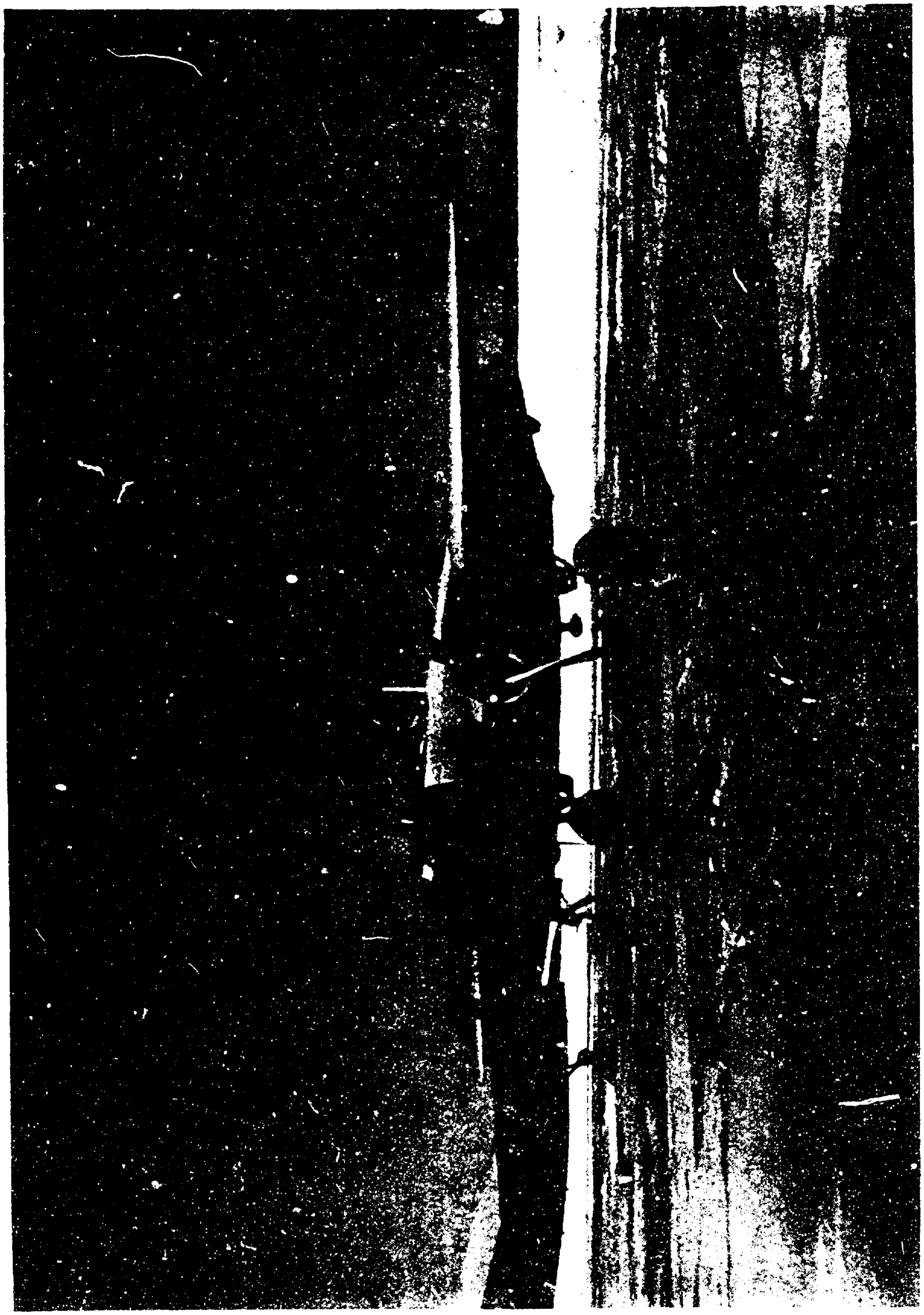

Figure 3-17. B-25 Aircraft

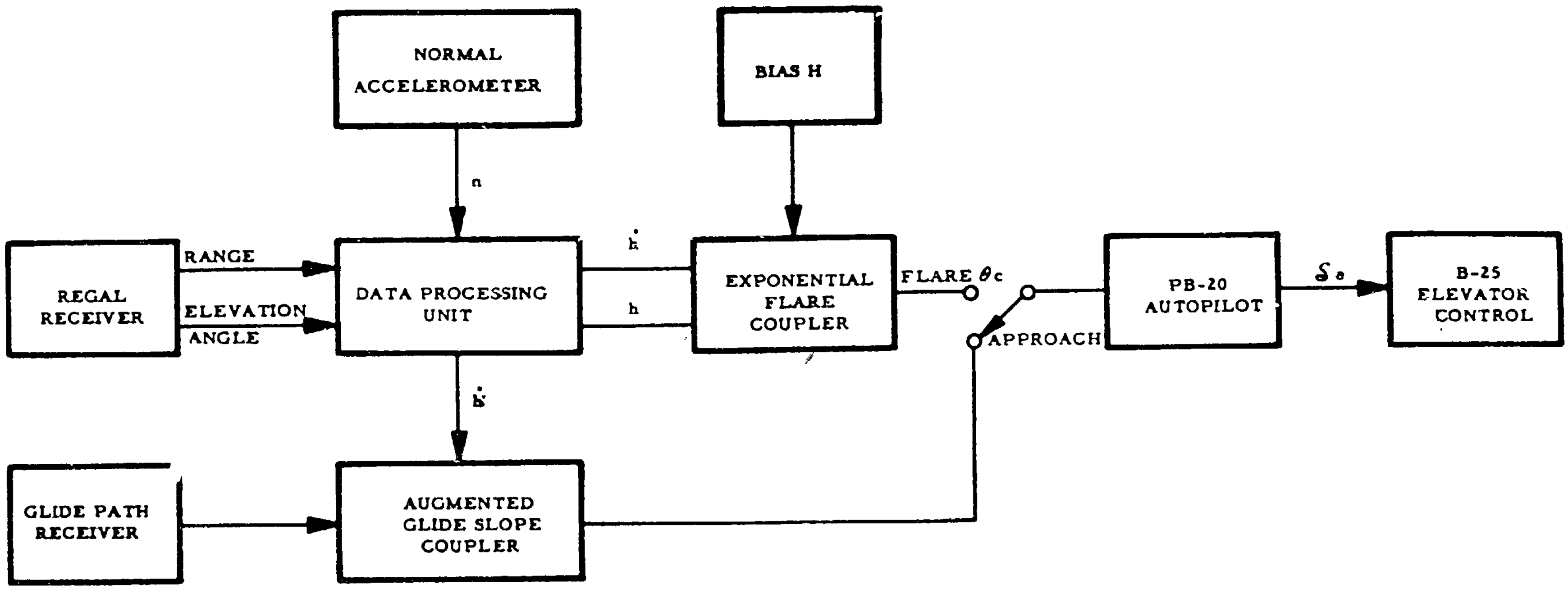

Figure 3-18. B-25 REGAL Landing Computer - Block Diagram

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The output of the exponential flare computer presents a pitch altitude command to the PB-20 autopilot. The autopilot has been slightly modified from the production configurations to achieve a somewhat faster time response.

3.1.5.4 Instrumentation Equipment. - The output signals from REGAL, together with the flight path computer and autopilot signals, were recorded on a Consolidated Electrodynamics galvanometer recorder. This type of recording did not provide a means of viewing the data until complete processing of the film was performed. Later when phototheodolite coverage was needed, a receiver capable of providing airborne NAFEC timing signals was installed and its output was recorded on one channel of this recorder. Generally the instrumentation available was quite limited, but considering the purpose of the flights it was adequate.

3.1.5.5 B-25 Cockpit Installation. - Instruments used for presentation of flight control data were of conventional and special types. The conventional instruments consisted of a standard flight director and a new tape dial indicator. Shown in Figure 3-19 is the special Bendix triple tape dial unit which displayed altitude, range, and vertical speed data derived from REGAL. This unit was specifically designed for use on this program, and provided the pilot with good indications of positions in space during the latter part of the approach through flareout to touchdown.

3.1.6 C131 Aircraft Installation. - This aircraft was equipped by the Sperry Phoenix Company under contract to the USAF Flight Control Laboratory for the REGAL program. During the testing program, aircraft support was provided by the Air Force. The aircraft was used for a two-week period in December 1961 to evaluate the Sperry computer system on manual controlled landings. Further automatic control testing was planned but these were abandoned due to problems of equipment modification and scheduling.

3.1.6.1 REGAL Equipment Installation. - In the installation of the REGAL antenna, a coaxial spiroline was used in lieu of a conventional waveguide because of the difficult routing problem. As shown in Figure 3-20, the REGAL antenna was mounted on the nose of aircraft, approximately 8.5 feet above the ground. The coaxial spiroline was then routed to the rear passenger cabin and into adapters connecting it to the REGAL receiver. The receiver was mounted, as indicated in Figure 3-20, on a conventional rack in the passenger cabin. Directly below this was located the Gilfillan coordinate converter unit. All units were easily accessible and adjustments in flight could be performed.

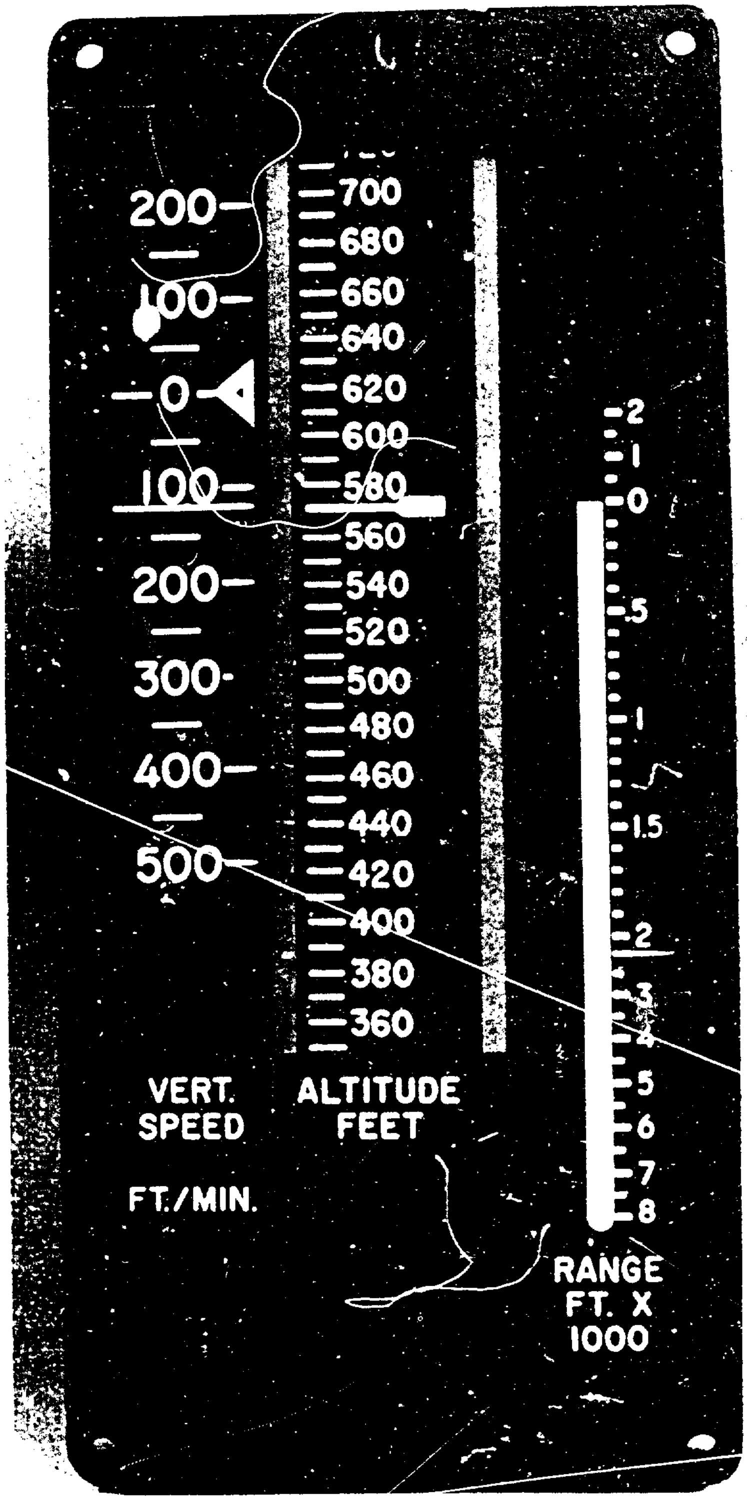

Figure 3-19. Bendix Triple Tape Indicator Unit

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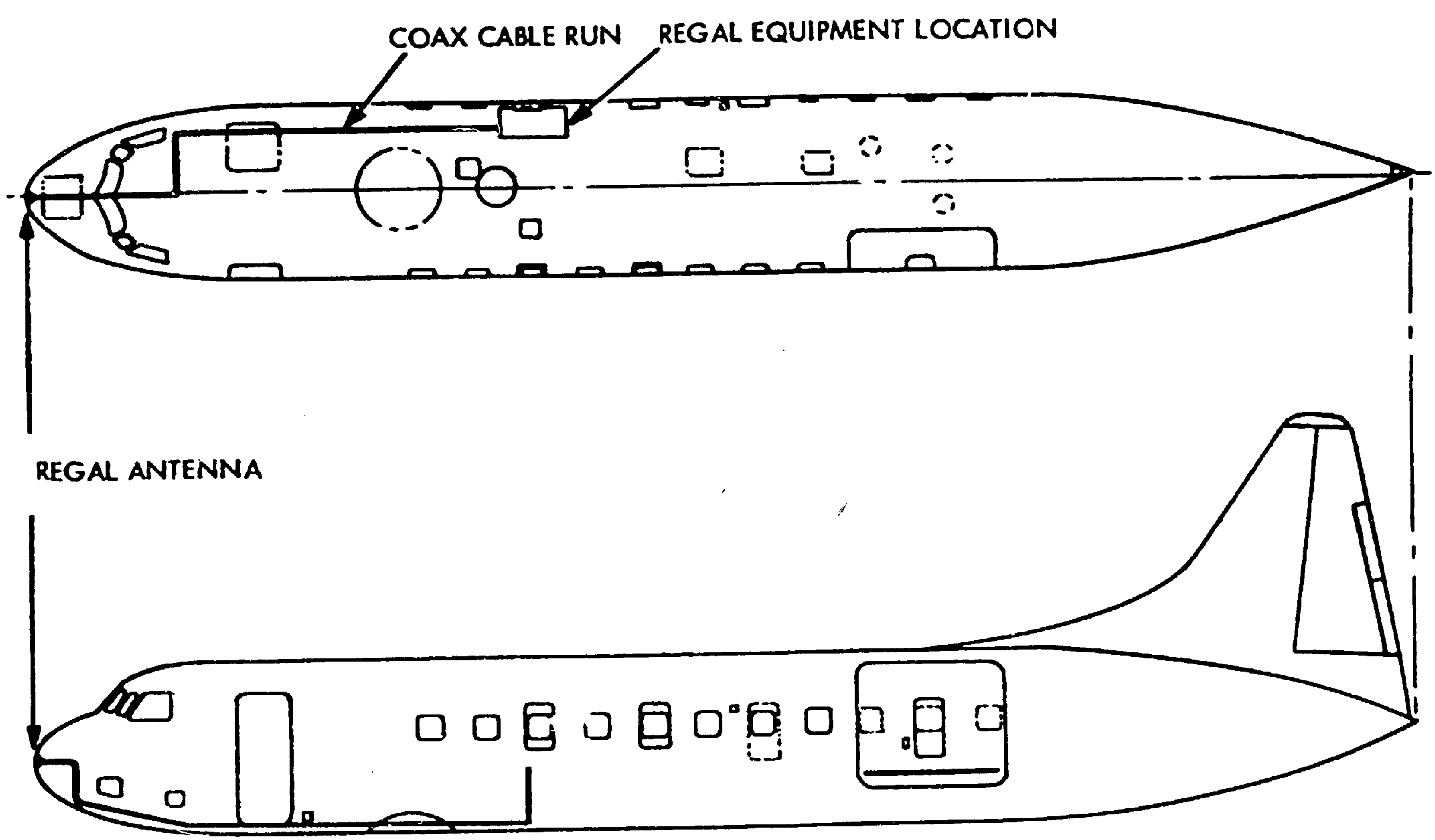

Figure 3-20. Receiver and Antenna Location - C131 Aircraft

3.1.6.2 Instrumentation. - A minimum amount of instrumentation was provided because at the time only qualitative data was under consideration. The recording apparatus was a Sandborn four channel recorder with inputs capable of being connected to any parameter desired. The recorder was used only when a signal needed to be analyzed for quality. No permanent data was gathered for the purpose of quantitative analysis.

3.1.7 T33 Aircraft Installation. - Early in the program installation of automatic landing equipment in a T33 aircraft was planned by the USAF. Some design and construction work was performed by Lear Incorporated. This effort was not completed due to funding and scheduling problems.

3.2 REGAL TEST RESULTS

The function of the experimental REGAL equipment was to demonstrate the technical feasibility of the REGAL technique and to serve as an experimental tool in demonstrating control of aircraft along flexible paths near the ground. The equipment provides guidance in only the elevation plane because this represents the most difficult problem area and because, with recent improvement, the ILS localizer offers promise of good lateral control in the near future. The test program was divided into four phases: Static Accuracy Testing, Dynamic Accuracy Testing, Manual Flight Control Testing, and Automatic Flight Control Testing.

3.2.1 Static Angle Data Accuracy Tests. - The static angle accuracy tests were made over a two-month period starting in the latter part of May 1960 and ending in the middle of July 1960. The objective was to make three runs at each survey point on each of three REGAL receivers and a larger number of runs at the touchdown point for correlation purposes. Although all of these were not achieved, a relatively large statistical sample of approximately 10,000 data measurements was obtained. The receivers were aligned before the start of the series and no further adjustments of any kind were allowed except in one case where a component failure necessitated readjustment. Using the static test truck, whose receiving antenna was adjustable to any altitude between two and forty feet, angle measurements were performed at more than 20 of the survey positions. These positions primarily concerned the touchdown zone at ranges from 500 to 2400 feet from REGAL. These positions were along the runway centerline and along both edges of the runway. For a particular measurement, the test truck was oriented over a known datum point. The antenna was adjusted in height increments of two feet and at least ten successive scans of the REGAL antenna were recorded at each height.

3.2.1.1 Data Reduction. - This data was then processed to determine the angular accuracies and coverage capabilities. The results of these tests were presented in the form of tabular data and graphs in the NAFEC Interim Report.

Tabular data was made available to Gilfillan so that a study could be performed to evaluate the results from the designer's viewpoint. This data was received and the following initial analysis was performed.

a. The tabular data was sorted, according to test date, to determine if there was any consistent change as a function of time. No trend was found and therefore data over the two-month period was combined irrespective of test date.
b. Runway centerline results on each receiver were statistically compared to that of the other receivers. Although the mean value of data from Receiver #4 was slightly different, the magnitude was not significant enough to impair combining data from the three different receivers.

As the data was evaluated, several runs exhibited gross errors consistent on all altitudes. In examining the heights and angles involved for the site, it was determined that errors existed in the survey data. Consequently, wherever practical, these runs were corrected for this discrepancy. It is believed these errors contributed a sizable error in data presented in the Interim Report.

The preliminary evaluation of the data showed that the following runs were not suitable for further statistical analysis.

a. Receiver #4 on 7-13-61 at 10:45 hours because of an obvious malfunction.
b. Receiver #4 on 7-5-61 at site 20* because of distinct non-repeating errors.
c. All data at site 30* because survey data was in error and no correction was obtainable.
d. All data at sites 29*, 19*, 9*, 518, and 28, because an insufficient statistical sample was obtained. These sites are at very short ranges (518 feet or less) and at extreme azimuth angles (greater than 25°).

The angle data recorded in the runs at the very short range sites mentioned in "d" above had a relatively large number of flags (data "bad" indications) and was more noisy than data at other sites. This was ascribed to the following factors:

a. The wall of the ground equipment shelter partially masked the signals from one of the transmitting antennas at the wide azimuth angles associated with these sites.
b. The null in one of the antenna patterns was slightly distorted at the wide azimuth angles.

c. The Receiver AGC adjustment technique used during these tests allowed some undesired saturation to occur at short ranges.
d. A safety circuit in the Beam Center detector card was designed to reject signals which had an excessively wide antenna beamwidth. A non-optimum adjustment of this circuit could have caused "data bad flags" to occur on otherwise good data.

After elimination of the data outside the region of interest and the invalid data, the remaining 120 data runs were analyzed. A few obvious errors were found in the data tabulation where the REGAL elevation angle was listed as 0.00 when apparently no data was recorded. These points were sorted out during the analysis.

There remained a number of data points which appeared to be errors made by the REGAL equipment. They represented approximately 8.7% of all the data, but only 5.2% of these were at elevation angles above 0.25% above the ground plane. More than 99% of the errors were identified by the "data bad" flag signal.

For the purposes of the analysis of system capabilities a second data sort was used which represents a validity check that may be easily included in the REGAL receivers. It is assumed that the present flag circuit is extended to reject data impulses and data with excessively high noise content.

This data sort excluded data as follows:

a. Flag count (data bad) equal to or greater than three out of ten samples.
b. Angle error perturbations equal to or greater than 0.25 degree.
c. Spread between successive samples equal to or greater than 10 bits (0.2^{o}).

The last procedure involved before reduction was to round off the designated surveyed angle to the nearest 0.001^{o}.

3.2.1.2 Data Normalization. - Previous theoretical studies[1] have shown that basic ground reflection phenomena for any system are a direct function of the angle of the receiving antenna above the mean ground plane. This was partially verified by several series of experimental tests as described in the above reference. Therefore, to obtain the most meaningful analysis of the REGAL test data, a mean ground plane was established and all data was normalized with respect to it.

The original data as received from NAFEC was on polar coordinate form referenced to a level line through the axis of antenna rotation. Many angles within the system coverage were negative with respect to the scan axis. This made it difficult to correlate the effects of the ground interference on measurements made at different ranges. The ground profile of the NAFEC test area was examined, with the runway area being of major concern, and it was established that the ground plane had a mean slope of 0.19 degree with the point of origin ten feet below antenna scan axis. This, therefore, became the plane of reference for all the data analysis and all elevation angles were converted to this reference.

3.2.1.3 Test Results. - Shown in Figures 3-21 through 3-28 are plots of REGAL angle accuracy versus elevation angle for sites along the runway centerline. Site 27 was included but it should be noted that this site is at an azimuth angle of almost 22 degrees and corresponds to the extreme limit of the touchdown dispersion zone of ± 500 feet. When the remainder of the sites are considered, the mean plots remain within the ± .05 degree tolerance down to 0.25 degree above the mean ground plane. To verify that lateral displacement did not appreciably influence the minimum coverage, survey points left and right of the centerline were included. Shown in Figures 3-29 through 3-31 are the combined data for the near side, far side and centerline of the runway. In each case very little difference in low angular coverage occured. Similarly all near side, far side points and center runway points were combined and their results are shown respectively as a function of range in Figures 3-32 through 3-34. The final study combined all runway sites and the results are shown in Figure 3-35. An analysis of all data above 0.25° above the mean ground plane resulted in a mean angle error of less than 0.005° and a standard deviation of less than 0.030°.

3.2.1.4 Angle Coverage Tests.- During the month of October 1960, a series of tests were performed to determine the coverage limits of the REGAL system. A total of 17 dynamic runs were performed utilizing the C-54 aircraft (BRAD 12). Primarily the procedure used was to fly the aircraft at various altitudes, approach bearings, and lateral offsets with respect to the REGAL centerline recording the data from REGAL on airborne brush recorders. Even marks were also provided to establish the aircrafts' position in range. For these tests the transmission of REGAL was confined to 10 degrees in the elevation plane. Results of these tests indicated that the lateral angular

[1] Final Study Report for Proposed Landing Control Set AN/GSN-6, FAA-BRD under AF30 (602)1765, Project 4527 Task 45047, Gilfillan Corporation.

Elevation Angle Error
Range 700 ft.
Site 27, Runway Center Line

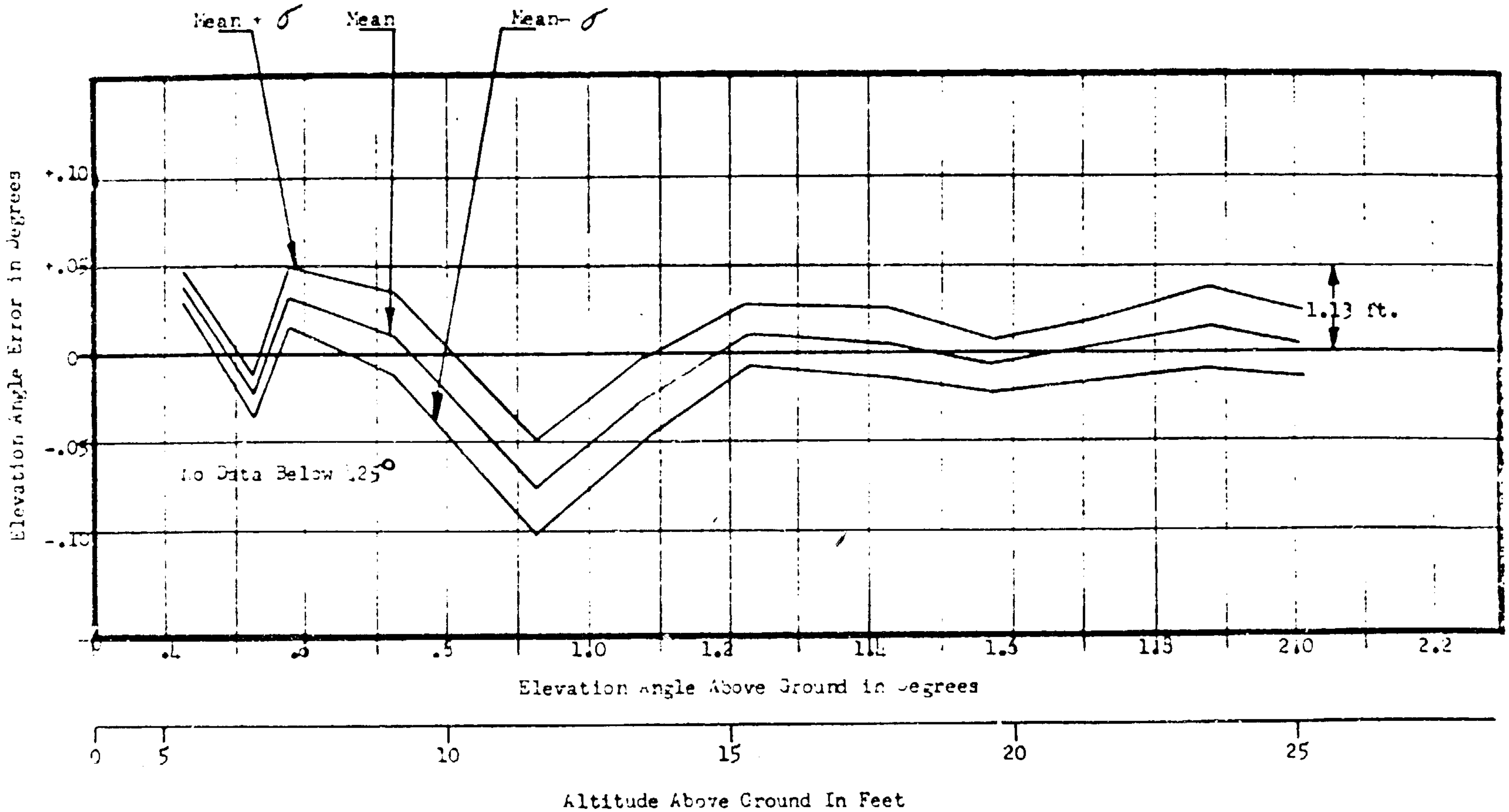

Figure 3-21.

Elevation Angle Error
Range 950 ft.
Site 26A, Runway Center Line

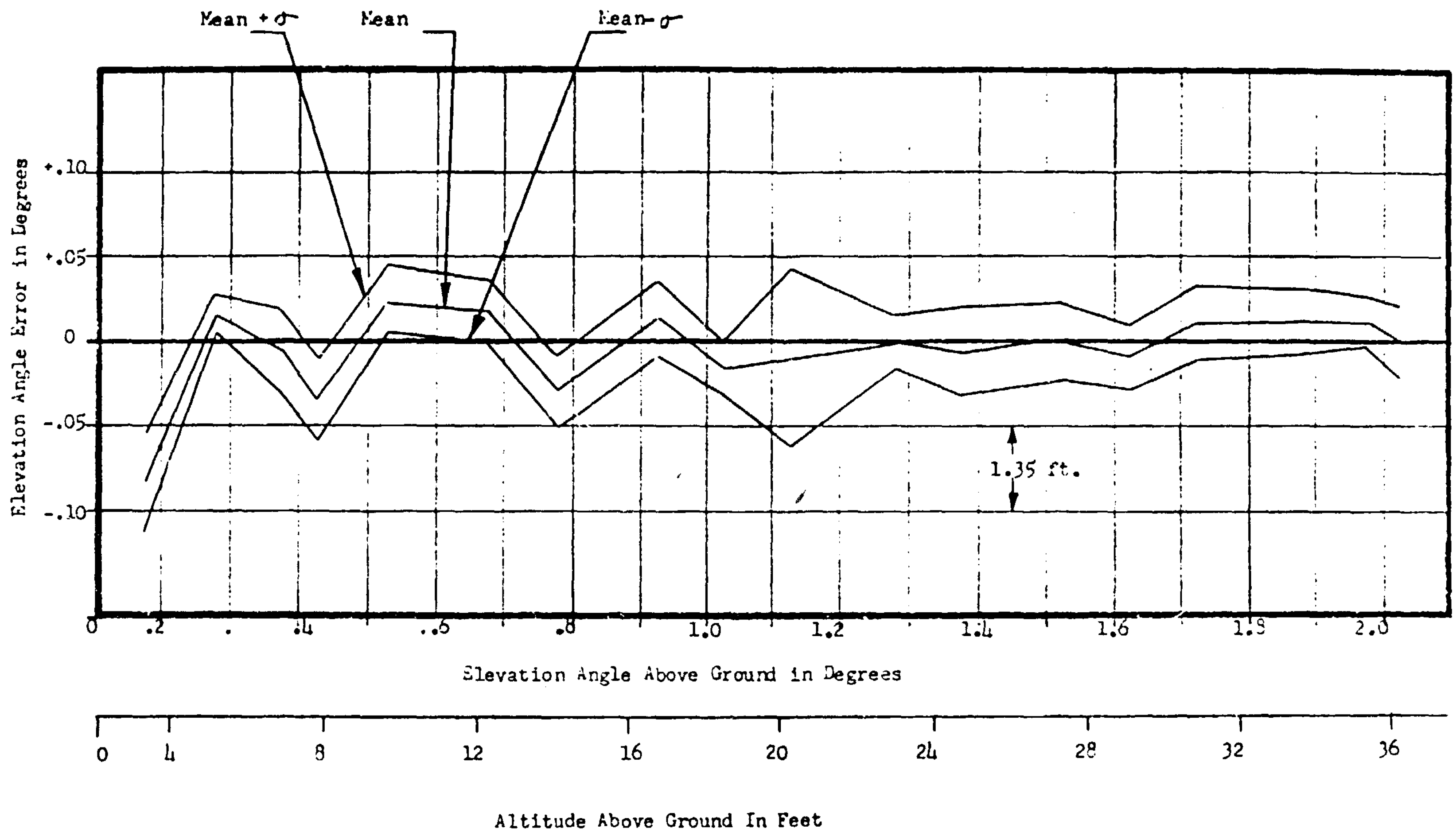

Figure 3-22.

Elevation Angle Error

Range 1200 ft.

Site 26, Runway Center Line

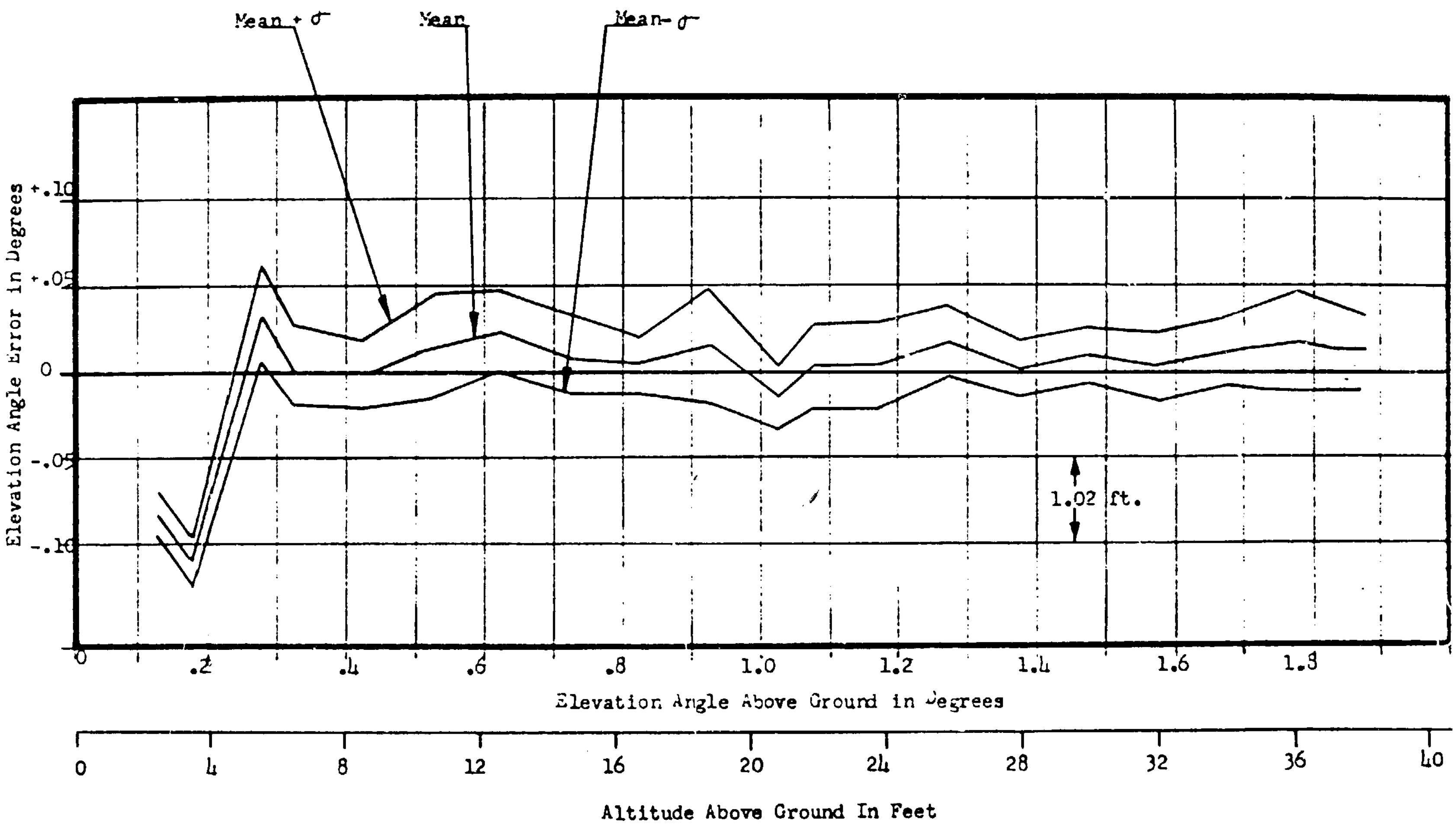

Figure 3-23.

Elevation Angle Error
Range 1450 ft.
Site 25A, Runway Center Line

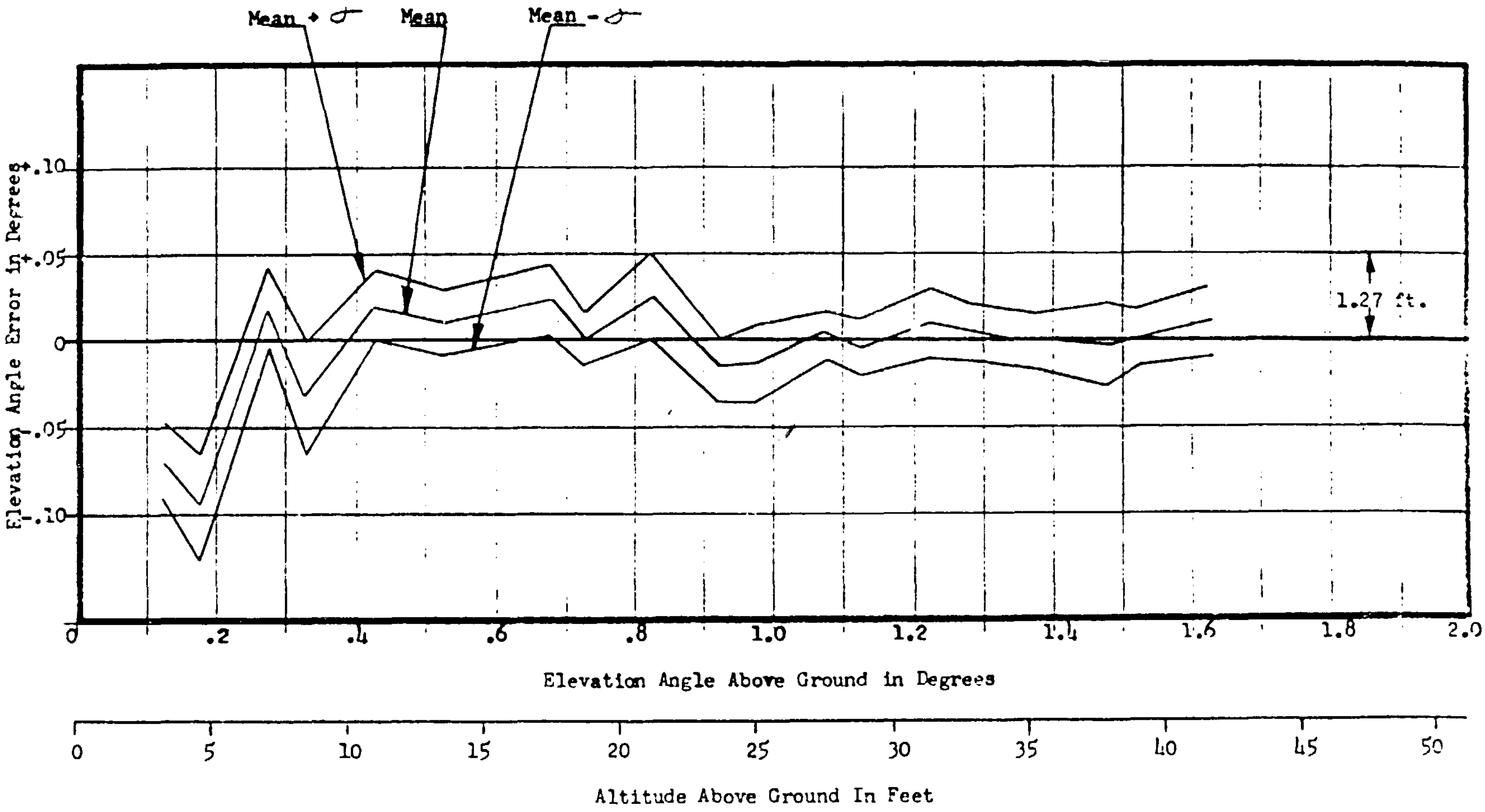

Figure 3-24.

Elevation Angle Error
Range 1700 ft.
Site 25, Runway Center Line

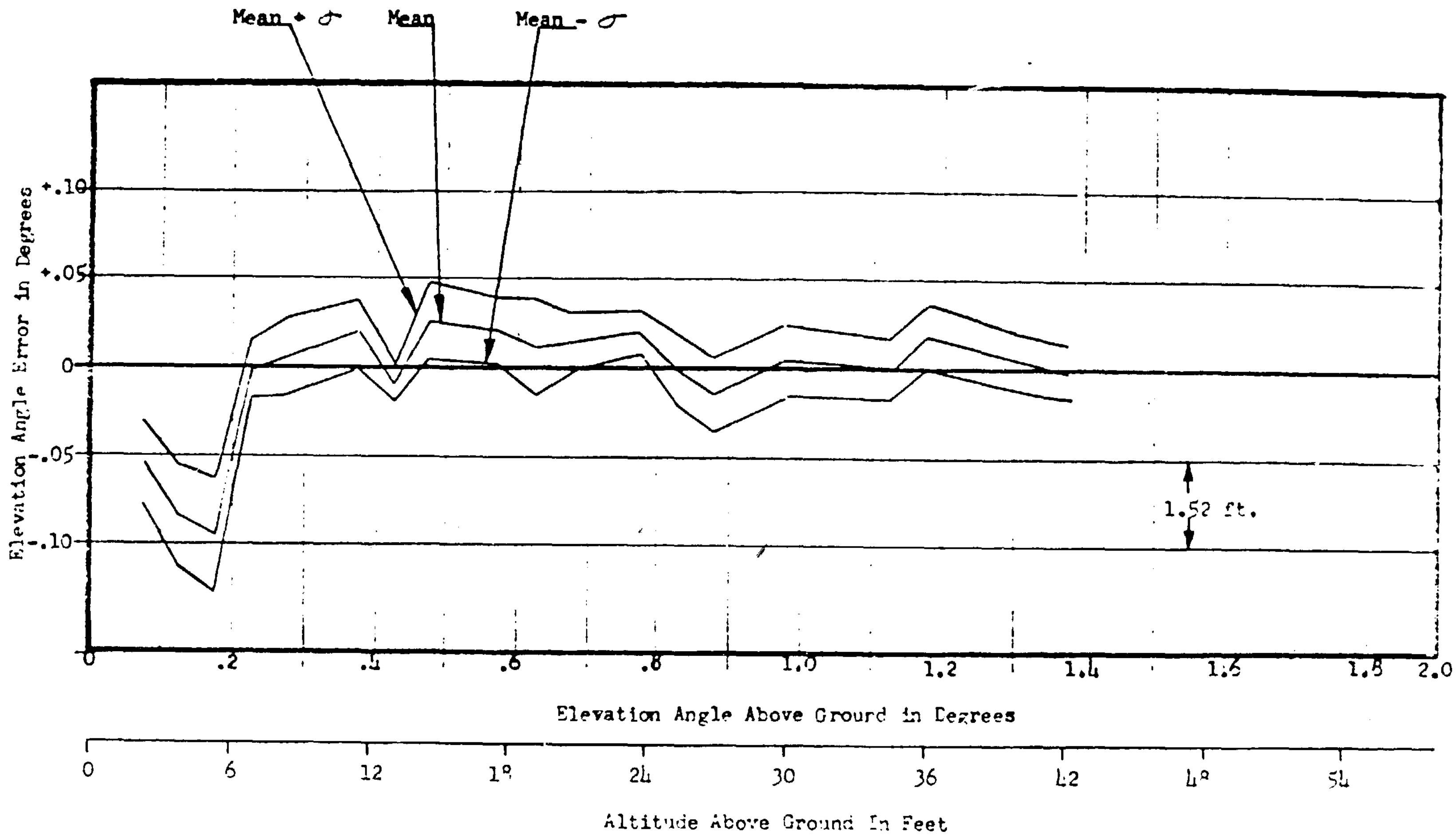

Figure 3-25

Elevation Angle Error
Range 1950 ft.
Site 24B, Runway Center Line

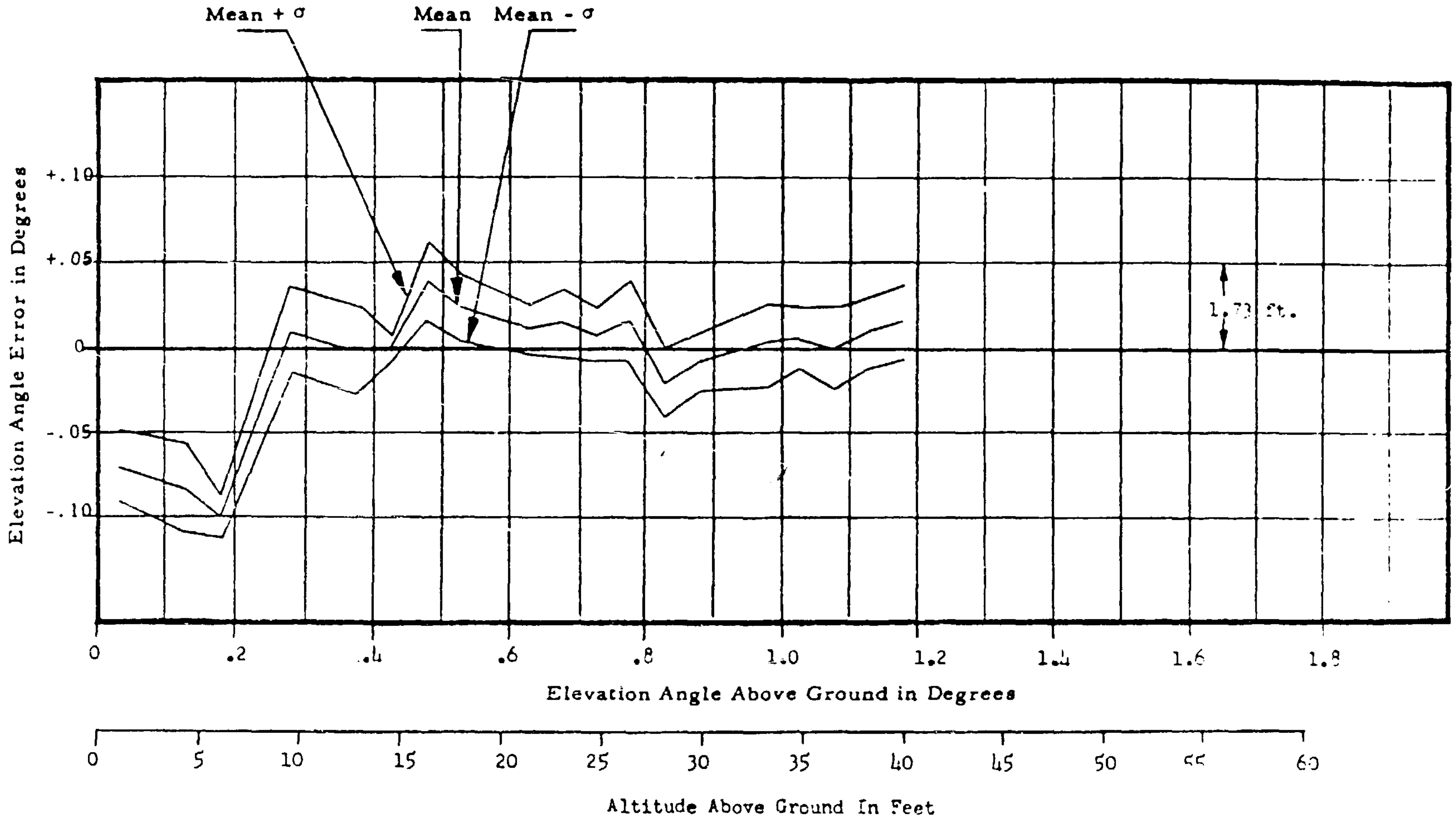

Figure 3-26.

Elevation Angle Error
Range 2200 ft.
Site 26, Runway Center Line

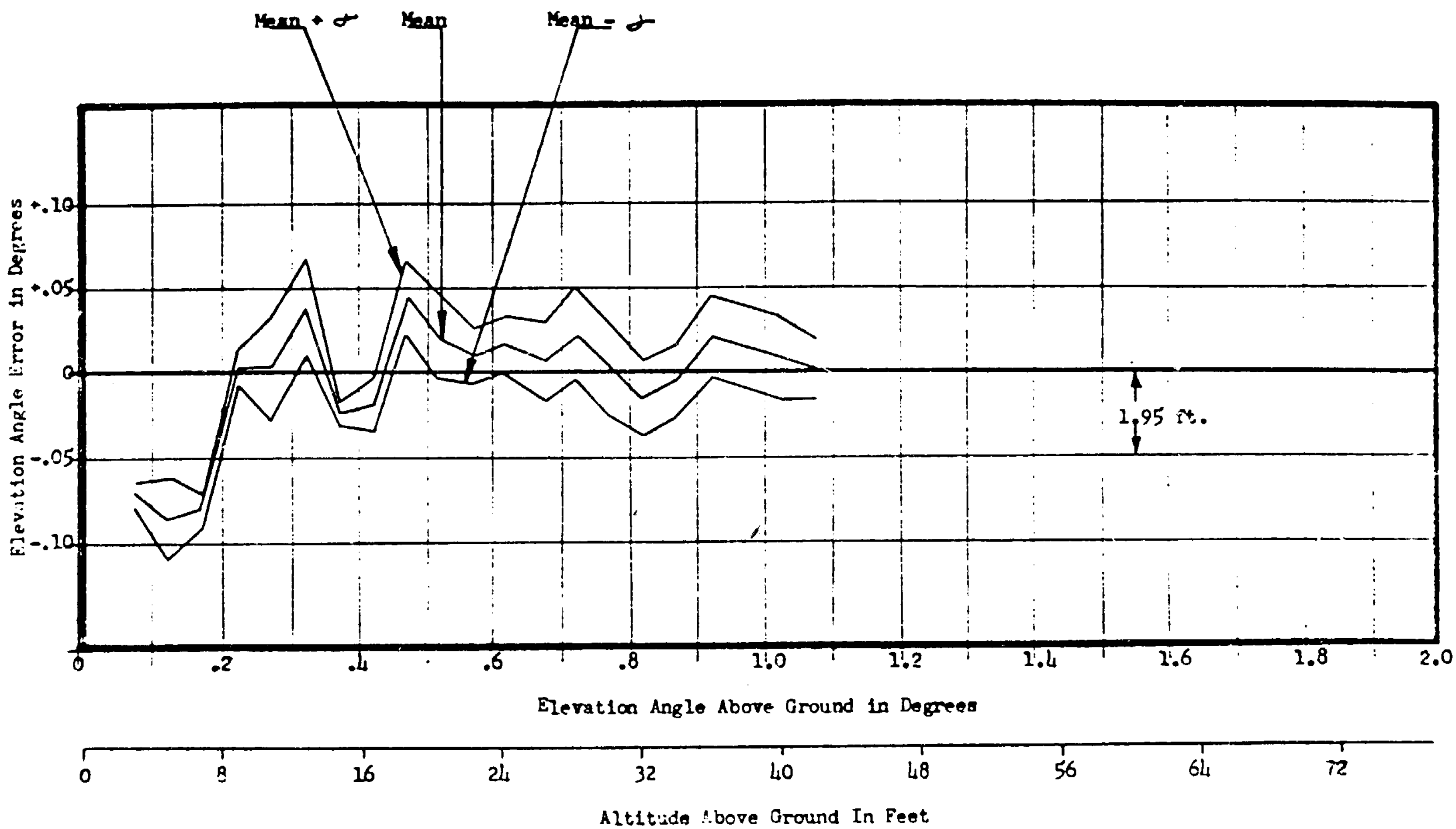

Figure 3-27.

Elevation Angle Error
Range 2500 ft.
Site 24, Runway Center Line

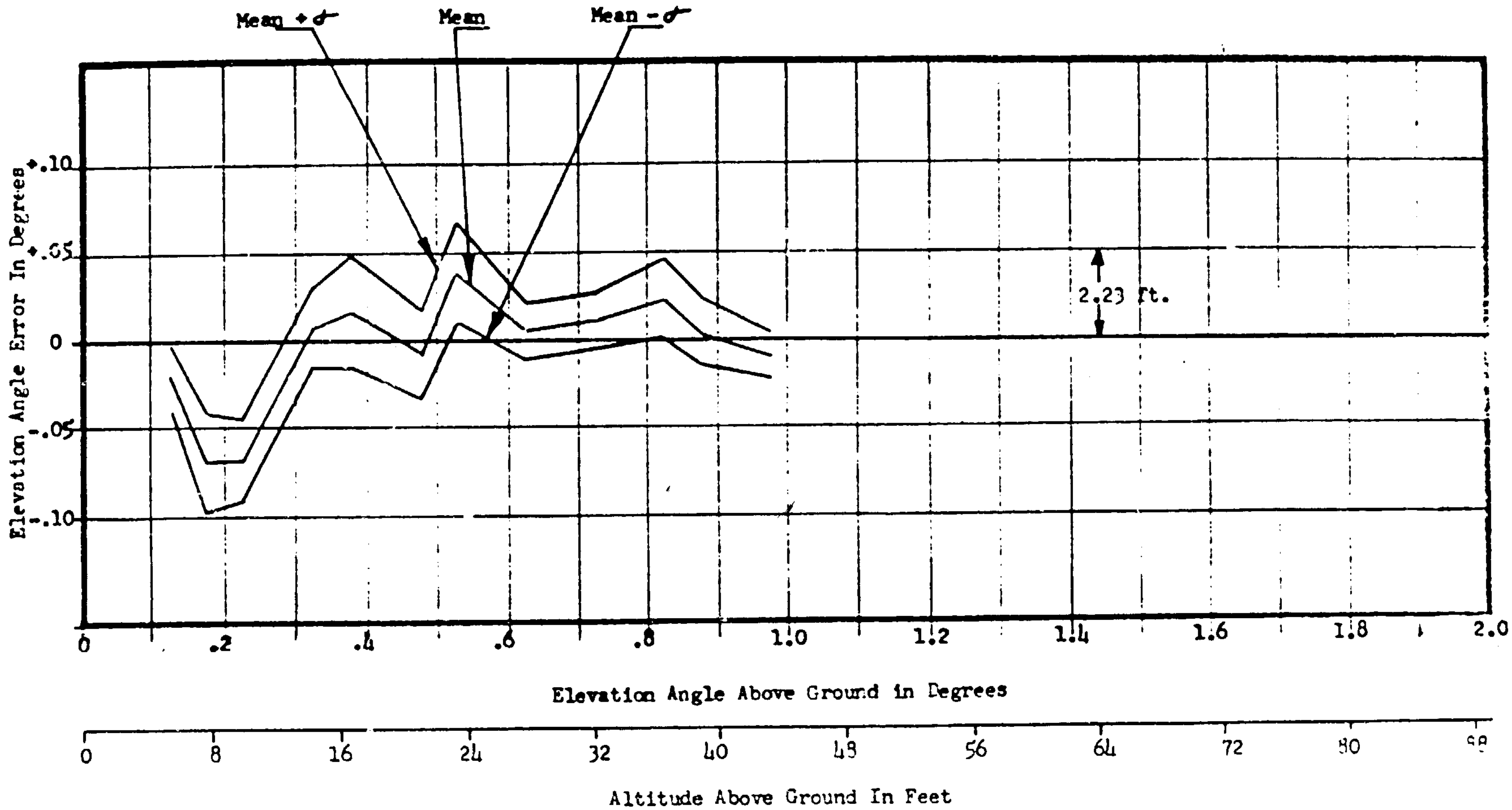

Figure 3-28.

Composite Angle Error
Range 1200 ft., Site 26, 21* and 31*
Center Line Left and Right

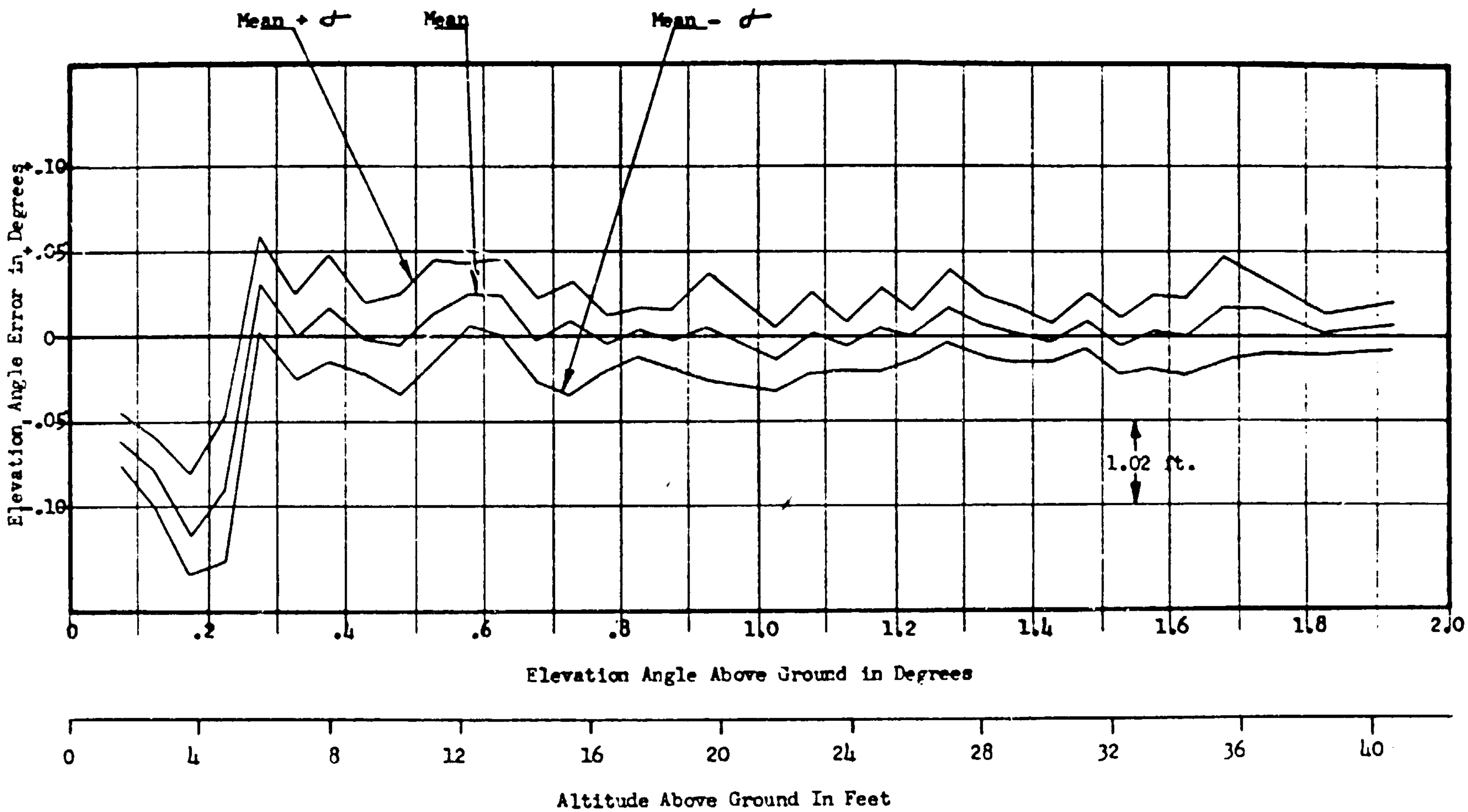

Figure 3-29.

Composite Angle Error
Range 1700 ft.
Sites 22*, 25 and 32*
Center Line Left and Right

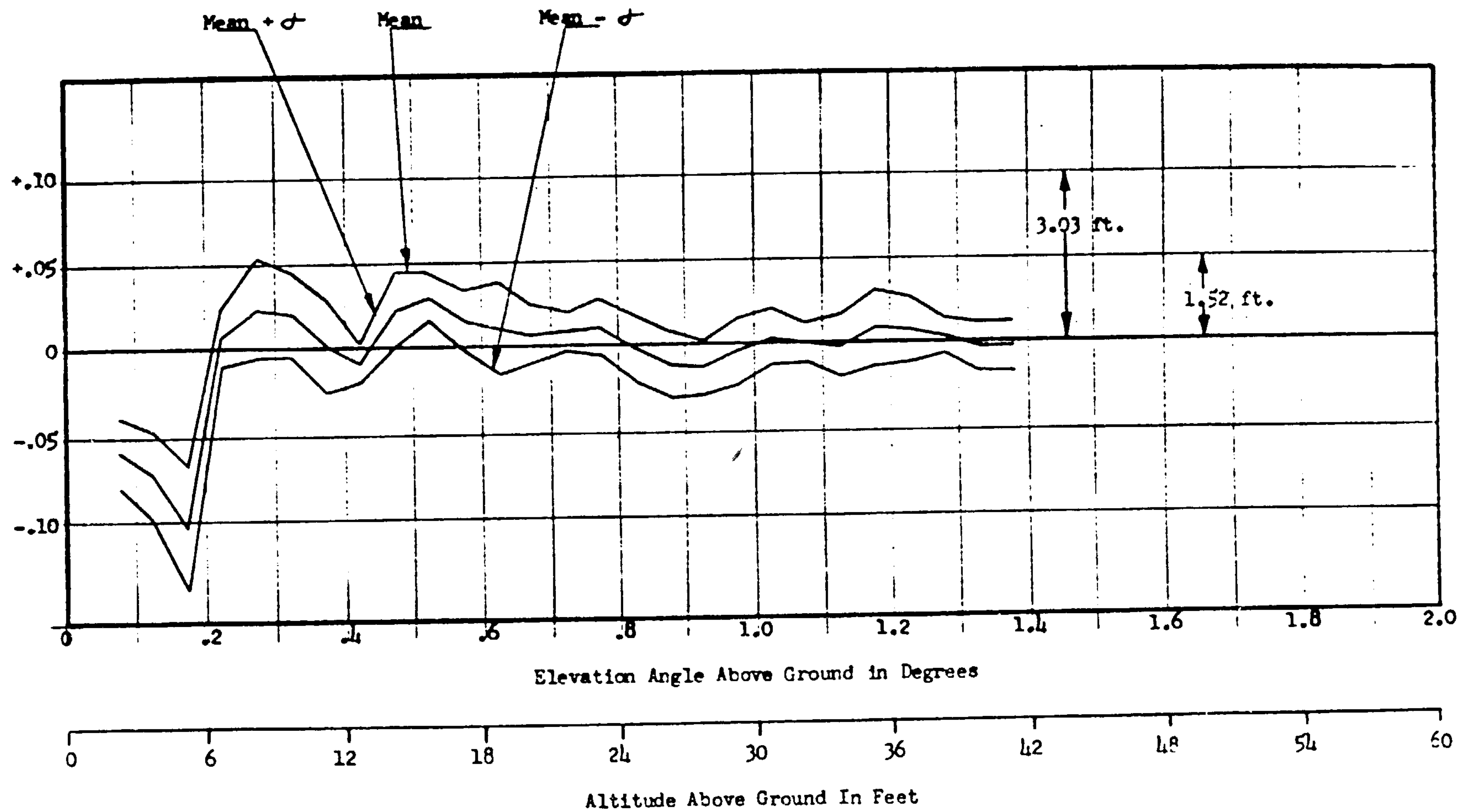

Figure 3-30.

Composite Angle Error
Range 2200 ft.
Sites 24 A, 22A* and 32A*
Center Line Left and Right

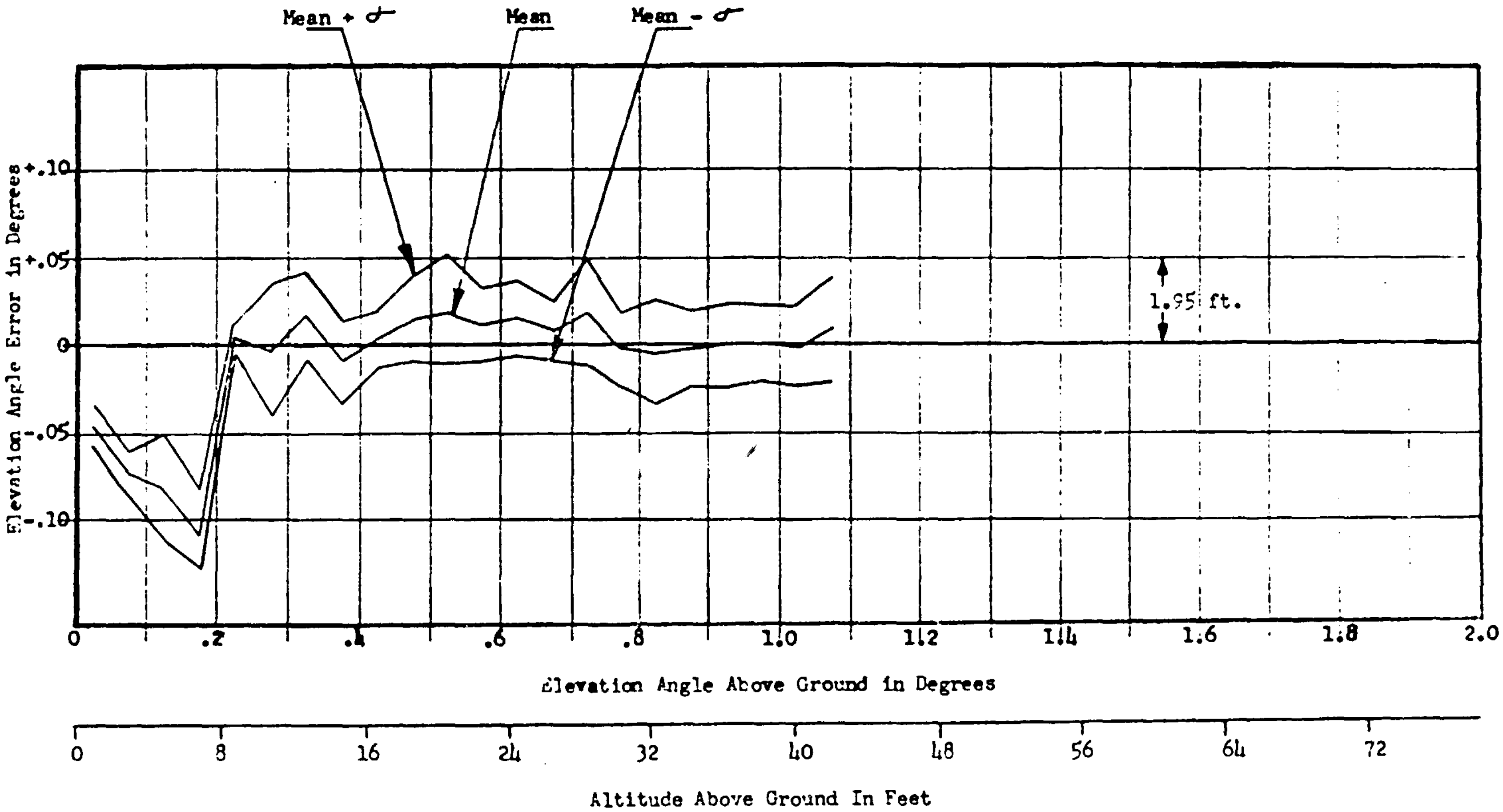

Figure 3-31.

Composite Angle Error Along Near Side of Runway
Range from 700 ft. to 2200 ft.
Sites 20*, 21*, 22*, and 22A

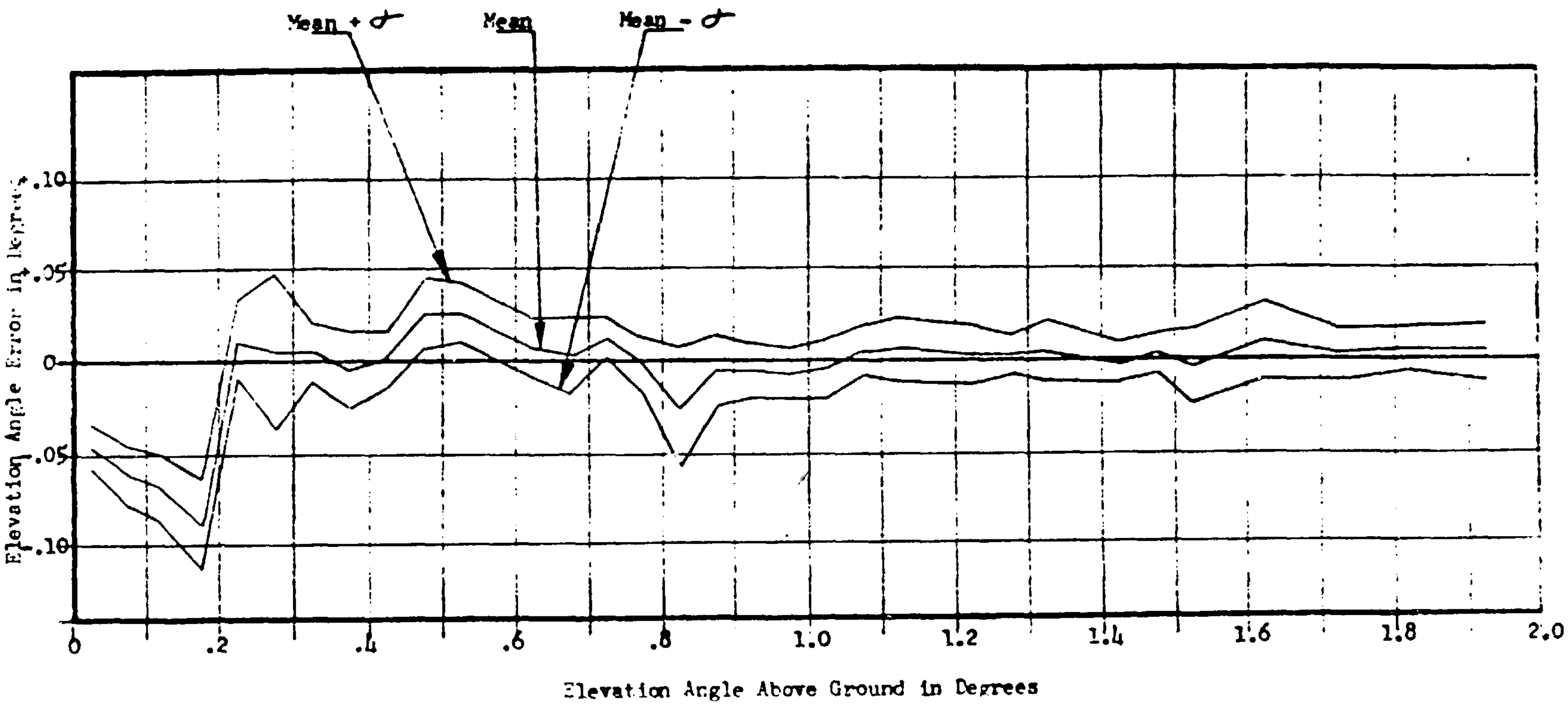

Figure 3-32.

Composite Angle Error Along far Side of Runway
Range from 1200 ft. to 2200 ft.
Sites 31*, 32* and 32A*

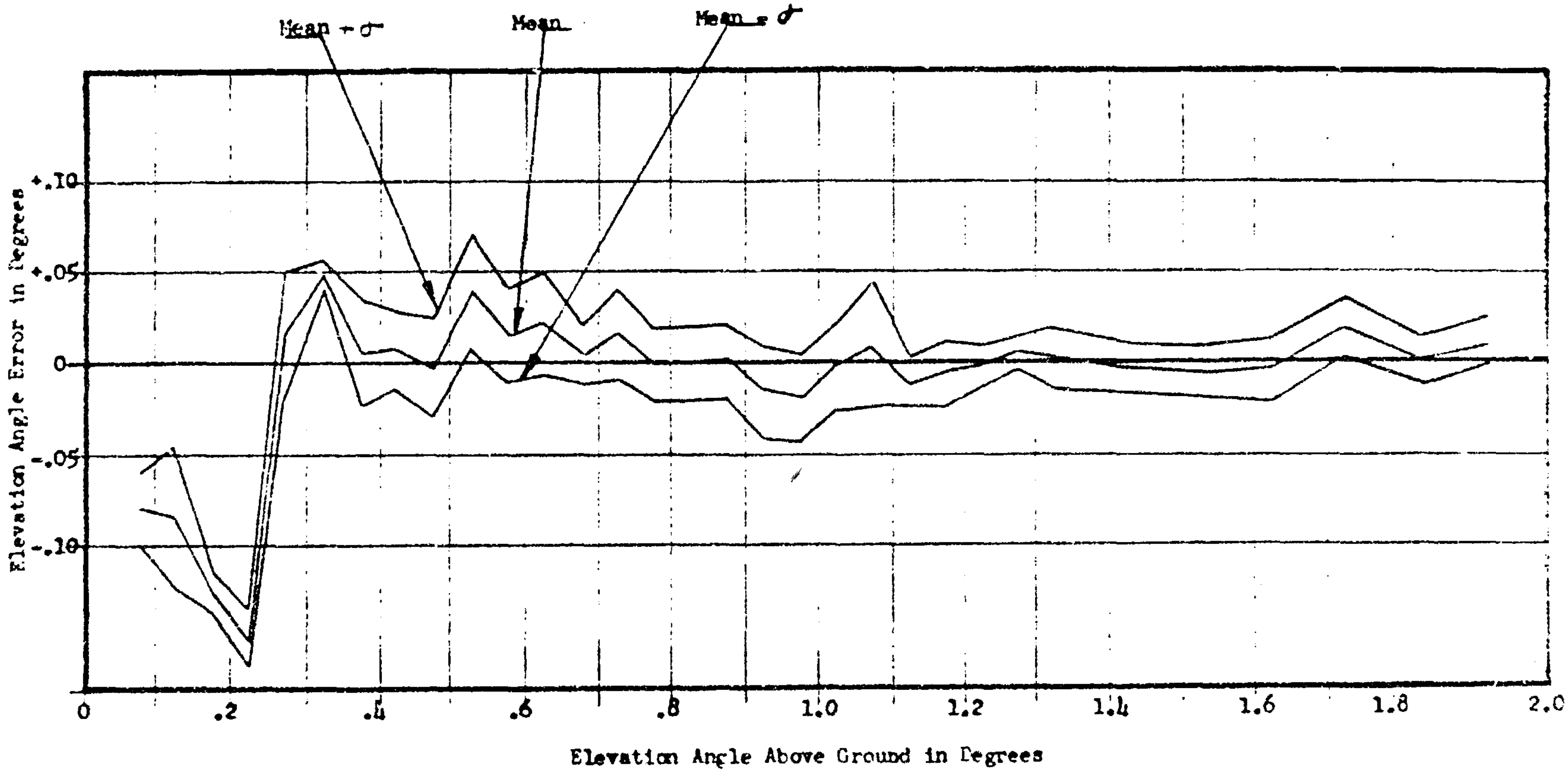

Figure 3-33.

Composite Angle Error Along Runway Center Line
Range from 700 ft. to 2500 ft.
Sites 24, 24A, 24B, 25, 25A, 26, 26A, and 27

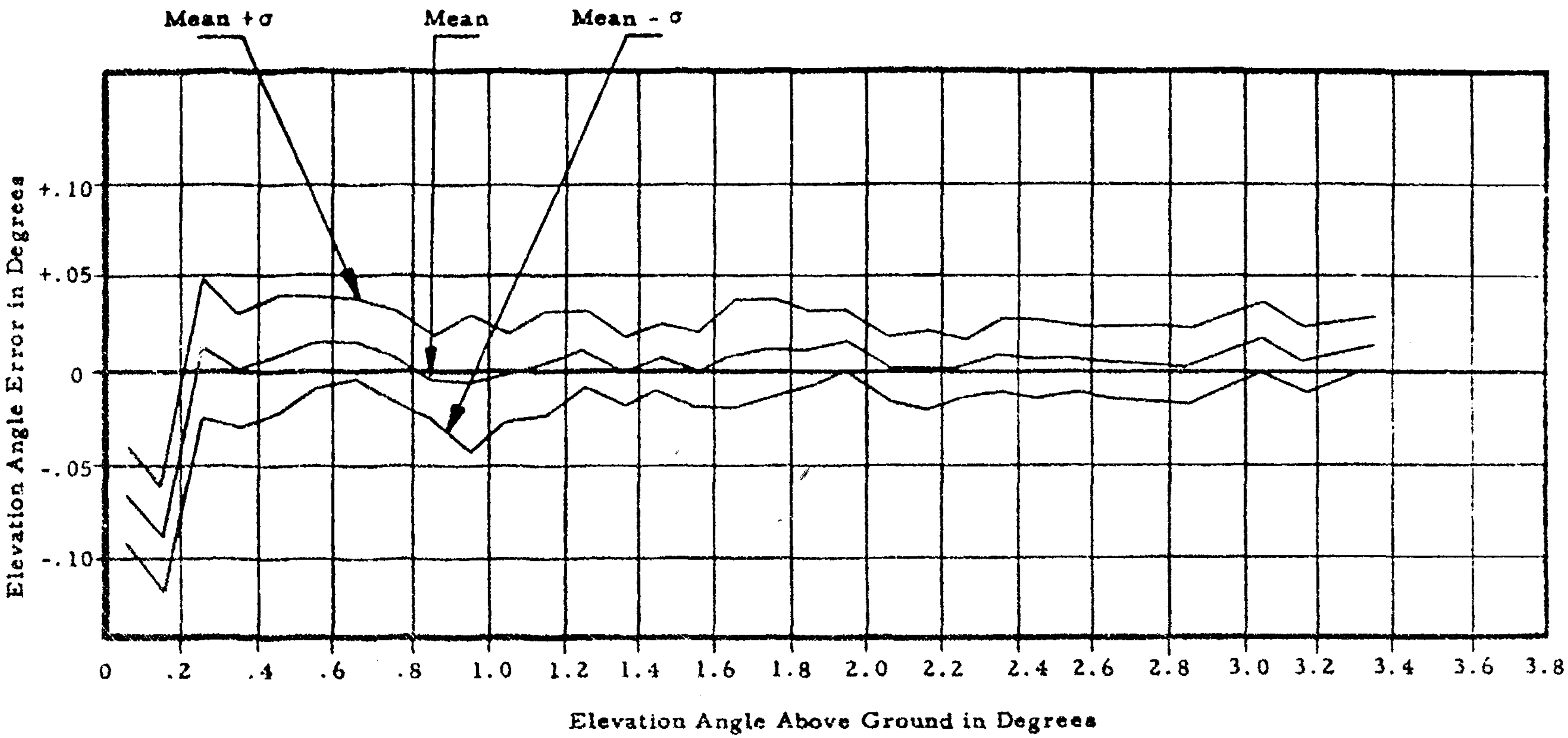

Figure 3-34.

Composite Angle Error All Sites Except
9, 19*, 28, 29*, 30 and 518

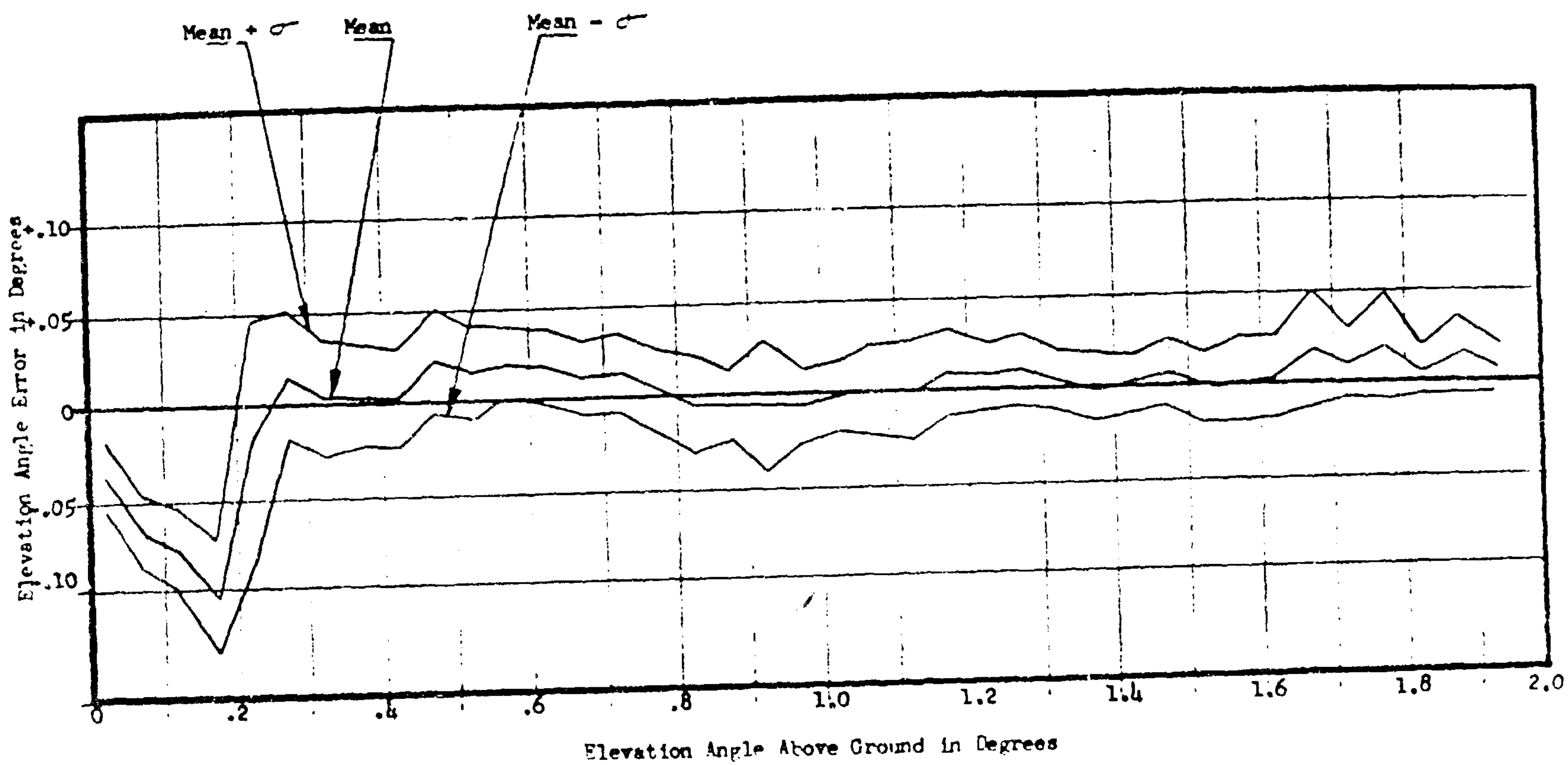

Figure 3-35.

limits in azimuth approached ±30 degrees with coverage at these extreme angles to a range of 16 miles. On the centerline of REGAL the angular data was available to ranges exceeding 20 miles. Elevation angle coverage was available up to approximately 9-1/2 degrees when the other limits specified were not exceeded. The minimum angle coverage of the system was found to be 0.25° above the ground plane as described in paragraph 3.2.1.3. This corresponds to an aircraft antenna height of less than six feet at the nominal touchdown point.

3.2.1.5 REGAL Angle Data Stability. - The testing program of REGAL at NAFEC included several efforts devoted to establishing the stability of the angle data system. During the static and dynamic accuracy tests no adjustments were performed unless a malfunction occurred. The units and the overall system were given periodic tests to establish the amount of drift being experienced. In addition laboratory measurements were performed on the receivers to investigate other stability factors.

During the two-month static angle data testing period in the summer of 1960, no adjustments were required on the ground equipment or the three receivers under test. Total system drift measured by any of the receivers during this test portion was significantly less than the system resolution of 0.02 degrees. During the dynamic testing from 22 March 1962 to 24 April 1962, no adjustments of repairs were performed on the REGAL equipment. No drift in the angle data measurements could be observed.

One area of stability investigated in the REGAL airborne receivers was the circuits involved with the digital to analog conversion. Special laboratory tests were performed covering a period of one year to evaluate the drift experienced in three receivers. It was found that for any digital code the stability of the output analog voltage on all three receivers was better than ±0.01 degree.

3.2.1.6 Static Angle Data Conclusions. - The following conclusion can be drawn from the results of the static elevation accuracy tests:

a. The mean angle error of 120 static tests runs, throughout the touchdown zone, was less than 0.005 degrees. The standard deviation was 0.030 degrees.

b. That the minimum angle coverage within prescribed accuracy above the calculated ground plane at all runway sites is 0.25 degrees.

c. That the azimuth angle coverage measured on the REGAL system at NAFEC exceeds the proposed coverage originally specified for the system. Data within the stated accuracy of .05 degrees is available at azimuth angles up to 22 degrees.

d. That the minimum range at which elevation data remains within the given accuracy on the runway centerline is 700 feet.

e. That the calibration procedures used provides a suitable alignment for different receivers.

f. That the receiver accuracy in angle did not deteriorate significantly over the duration of testing.

g. That the "data good circuits" provide a very high confidence level for rejecting non-usable data.

3.2.2 Static Range Measurements. - During the time that the static angle data was being gathered, some measurements were performed on the range parameter. These measurements were not considered at the time to be significantly important, which resulted in a very small sample of data being gathered under very poorly controlled conditions. After examining the results of these tests, it was decided that a new series of tests concerning only the range parameter would be performed. These measurements were conducted on four REGAL receivers during the period of May 2 to June 23, 1961. The tests were performed using the REGAL test van on NAFEC's taxiway "B" and runway 13-31 known survey ranges. To gather as many measurements as could be obtained in the shortest period of time possible, it was decided to acquire the data with the test truck moving from maximum to minimum range at a speed of approximately ten mph. The reduced data was corrected for short range errors as the test van was driven at a slight offset to the surveyed sites. Correction was also made for the time delay introduced by the electrical length of the antenna lead-in cable.

During the period of testing the four REGAL receivers initial calibration was not disturbed (i.e., no readjustment of internal controls). Before and after each series of three runs, a respective "pre" and "post" calibration was made not only to justify drifts occurring during the actual runs but also to indicate possible day to day shifts elsewhere in the system. The three runs involved performing the first two on the taxiway with the last one on the runway. The results presented in this report are primarily based on the error averages of data gathered on 38 test runs. These results are derived from data furnished from NAFEC which was corrected for all known offset errors except for initial calibration offsets.

3.2.2.1 Data Analysis. - The original data as obtained from NAFEC was subjected to analysis in an attempt to derive some meaningful conclusions. As received, the initial results of the 38 runs indicated the following:

a. The data taken on the three successive runs which comprised a test was generally in good agreement.
b. There was generally very poor correlation betweeen the bench calibration made in the laboratory and the dynamic data taken on the runway. The average difference was 86 feet.
c. The test data exhibited large variations between the receivers over the two-month testing period.

The following processing of the range accuracy data was performed in an attempt to derive some useful results.

a. The statistical accuracy figures were derived for the receivers based on the data received from NAFEC.
b. Since there appeared to be a predictable difference between the results obtained from the different receivers, an average calibration or setup error was calcualted for each receiver. These setup errors are shown in Table 3-1. Another set of accuracy figures was then derived after removing the average setup error.
c. Upon replotting the accuracy data after removal of the setup errors, a common drift with time was observed. This common system drift was subtracted from the data and a third set of accuracy figures were calculated.

Table 3-1. REGAL Reciever Range Accuracy Data

Receiver Number	Date	Average Error (Original Data)	Average Error (Setup Error Removed)	Average Error (Setup and Common Drift Error Removed)
		In Feet	In Feet	In Feet
1	5-22	133	70.6	24.7
	6-14	58	261.6	271.2
	6-15	248	44.4	32.3
	6-15	223	19.4	5.3
	6-19	194	9.6	32.5
	6-19	221	17.4	5.0
	6-19	202	1.6	24.5
	6-22	306	102.4	72.6
	6-23	363	159.4	127.1

Table 3-1. REGAL Receiver Range Accuracy Data (Cont'd)

eceiver umber	Date	Average Error (Original Data)	Average Error (Setup Error Removed)	Average Error (Setup and Common Drift Error Removed)
		In Feet	In Feet	In Feet
2	6-12	22	99.2	93.9
	6-14	24	101.2	91.6
	6-14	- 157	- 89.8	100.9
	6-15	- 163	- 95.8	- 109.9
	6-15	- 200	- 132.8	- 144.9
	6-19	- 124	- 55.8	- 78.2
	6-19	- 81	- 13.8	- 37.2
	6-22	21	88.2	57.9
	6-23	53	120.2	87.9
3	5-22	64		
4	5-9	- 80	- 28.9	48.8
	5-19	- 181	- 129.9	- 75.7
	5-25	- 81	- 29.9	8.6
	6-6	- 45	5.1	14.1
	6-7	- 70	- 18.9	- 11.8
	6-12	- 107	- 55.9	- 60.6
	6-13	- 26	25.1	17.9
	6-14	- 13	38.1	27.5
	6-15	- 53	- 1.9	- 14.0
	6-15	- 17	- 25.9	- 40.0
	6-22	20	71.1	41.8
	6-23	100	151.7	118.8
5	5-9	59	13.0	91.7
	5-18	- 21	- 67.0	- 10.3
	5-22	23	- 23.0	22.3
	5-24	50	4.0	45.4
	5-25	- 21	67.0	- 29.0
	6-15	101	55.0	40.9
	6-22	89	43.0	13.7
	6-23	88	42.0	10.2

The results of five of the 38 tests were observed to be less credible than the other data. In one case, there was a 300 foot change in the run average from one day to the next which appears to represent a severe malfunction. In the other cases there was greater than an 80 foot discrepancy between the respective pre-calibration and post-calibration tests. This also appeared to indicate a malfunction or measurement error. A fourth set of accuracy figures was derived after the elimination of the five suspect test results. The final results of this fourth group are shown in Table 3-2.

3.2.2.2 Static Range Accuracy Conclusions. - The following conclusions can be drawn from the results of the static range accuracy testing.

a. There is a definite need for a better means of calibrating REGAL receivers. This is indicated by the general lack of correlation between static accuracy tests and the bench calibrations. Whereas the bench calibrations indicated that all receivers were relatively well aligned, the test data indicated average setup errors from +203 feet to -67 feet in the extremes.
b. Without a more suitable bench calibration setup, the combined range accuracy and stability of all the REGAL receivers is approximately 136 feet RMS.
c. If a suitable bench calibration setup were available, a REGAL receiver range accuracy of approximately 80 feet RMS could be obtained.
d. There appeared to be a common drift during the period of the range accuracy tests due either to variation in the REGAL ground equipment or possibly due to variation in the testing equipment.
e. Elimination of the results of the five tests, which showed indications of receiver malfunction, made a significant improvement in the receiver accuracy numbers. It can be assumed that more reliable equipment of an equivalent design would exhibit better accuracy.

A subsequent check of the REGAL range accuracy and stability was obtained for one receiver between 22 March 1962 and 6 April 1962 in conjunction with dynamic accuracy tests. Calibration checks were made in the laboratory and the mobile test truck (no adjustments were allowed) before each flight. When the known 0.2 microsecond setup error was removed, average calibration error was 17.5 feet. The RMS drift of the laboratory tests was 14.5 feet and the RMS drift for the static measurements was 15.5 feet. This improved performance is ascribed to better alignment procedures and measurement techniques. The inherent accuracy plus stability is probably better than 50 feet RMS.

Table 3-2. REGAL Receiver Range [illegible]

Receiver Number	RMS Error (Original Data)	Setup Error	RMS Error (Setup Error Removed)	RMS Error (Setup Error & Common Drift Removed)	RMS Error (Setup Error Common Drift & Bad Points Removed)
	In Feet	In Feet	In Feet	In Feet	In Feet
1.	232.1	203.6	111.6*	104.6	55.7
2.	114.2	-67.2	94.6	94.0	81.0
3.	64.0				
4.	74.8	-51.1	66.3	51.3	51.3
5.	64.5	46.0	45.2	41.7	44.1
All Receivers	136.2		83.0**	76.5	59.1

*This RMS error becomes 74.0 feet if test data of 6-14 on Receiver #1 is excluded.

**This RMS error becomes 72.4 feet if test data of 6-14 on Receiver #1 is excluded.

3.2.3 Dynamic Accuracy Tests. - The primary method used to measure the dynamic accuracy of the REGAL system involved flights with the C-54 aircraft carrying the REGAL airborne components. This aircraft's position was measured by means of the NAFEC photo-theodolite tracking system. The tests were performed using a test plan similar to that shown in Table 3-3. The aircraft was flown manually along a number of difficult approach angles and constant altitude traverses. Three receivers were used for most types of tests.

Prior to presentation of the results, a comment is in order on the instrumentation system and techniques. Each item of instrumentation equipment was in general rated to have an accuracy capability of the same order of magnitude as the REGAL system. When this equipment was operated within a complicated instrumentation system for gathering large quantities of data on a dynamic problem, the over-all accuracy achieved is felt to be definitely marginal. For example, the photo-theodolites would probably be adequate for a small series of static tests but are questionable in view of the large quantity of film reading, the complex data reduction, and the difficulty in synchronizing them with the airborne recordings. Also, the accuracy of airborne recording galvanometers becomes questionable in view of the large quantity of data taken, the elaborate needs for calibration, scale changing, scale distending and time synchronization. A considerable amount of effort was expended to cross-check data from alternate sources and to justify a number of discrepancies in the final results. This is not to imply that no valid data was obtained, but it must be understood that the validty of the results is significantly clouded by errors in the basic instrumentation.

A detailed analysis of the data was not attempted for this report, because of the small statistical sample and because the final data reduction was not available. A brief summary of the dynamic test results as presented is indicative of the fact that no significant degradation of the static test results was found.

3.2.3.1 Dynamic Angle Tests. - The angle accuracy of the REGAL system under dynamic conditions was evaluated by comparison of angle data recorded on the Visicorder and the reduced photo-theodolite position information. There were a number of problems in reduction and coordiante transformation of the theodolite data but it is felt that these have been minimized to an acceptable level. Further effort was in process subsequent to Gilfillan receipt of the test results to refine other minor discrepancies in the data processing. The only remaining area of a possible problem is due to the difference in the REGAL scan rate and the photo-theodolite sample rate. Since these were not synchronized, the time difference between REGAL data and the photo-theodolite position data could introduce appreciable errors under conditions of relatively high rates of change of REGAL angle.

TABLE 3-3. DYNAMIC ACCURACY TESTS

Test 1 Level Flight	Runs
Use C-54 Control Receiver Serial #5, 1000 foot level flight, 15 NM, 160 kts IAS.	
(a) C/L	1
(b) ± 12 degrees	2
(c) ± 24 degrees	2
Use C-54 Control Receiver Serial #5, 2000 foot level flight, 15 NM, 160 kts IAS	
(a) C/L	1
(b) ± 12 degrees	2
Use C-54 Control Receiver Serial #5, 4000 foot level flight, 15 NM, 160 kts IAS	
(a) C/L	1
(b) ± 12 degrees	2
Use C-54 Control Receiver Serial #5, 8000 foot level flight, 15 NM, 160 kts IAS	
(a) C/L	1
Repeatability Flights	
Serial #3 Receiver C/L, 15NM, 160 kts IAS	
(a) 2000 foot altitude	1
(b) 4000 foot altitude	1
(c) 8000 foot altitude	1
(d) 1000 foot altitude	1
Serial #4 Receiver C/L, 15NM, 160 kts IAS	
(a) 1000 foot altitude	1

Test 2
Variable Approach Angles

Use C-54 Control Serial #5 Receiver, 110 kts IAS, C/L only
(a) Manual Approaches at angles 1.0 degrees through 5.0 degrees at .5 degree increments.
(b) Approaches to touchdown to be conducted manually as practicable, the pilot to flare the aircraft at sufficient altitude as to be able to make a low pass over the runway at an altitude of 40 feet above the REGAL site elevation.

TABLE 3-3. DYNAMIC ACCURACY TESTS - (Cont'd)

Test 2 (cont'd) Variable Approach Angles	Runs
Use Serial #3, 4, and 5 receivers and conduct C/L manual controlled approaches at the angles and airspeeds indicated below for each receiver:	
2.6°: 110 kts, 160 kts, 210 kts; 5.0°: 110 kts, 160 kts, 210 kts	
Note: Touchdown as practicable, pilot to flare aircraft at sufficient altitude as to pass over the runway at 40 feet above the REGAL site elevation.	18
Use C-54 Control Serial #5 Receiver, fly manual approaches at a 2.6 degree angle, as follows:	
± 12°: 110 kts, 210 kts; ± 24°: 160 kts	6

A typical result on one run is shown in Figure 3-36. Shown below are the results of several runs which appear to be relatively valid.

Run#	Angle Mean Error in Degrees	Angle Standard Deviation in Degrees
410	0.0029	0.0426
411	0.0097	0.0510
418	0.0145	0.0375
424	0.0277	0.0433
431	0.0100	0.0750
439	0.0109	0.410
449	0.0263	0.1240
456	0.0160	0.0481

It can be observed that the mean errors are less than 0.03 degree. The standard deviation of all runs except run #449 is in the order of 0.05 degree. An inspection of the data available from run #449 offers no clue concerning the unusually high standard deviation. It appears reasonable to assume that this is not representative of the basic system capabilities but is most likely due either to a partial equipment malfuction or some unidentified discrepancies in the instrumentation.

The difference between a standard deviation in the order of 0.05 degree obtained in the dynamic testing and 0.03 degree obtained from the static testing could be caused by a number of factors in the over-all instrumentation of the system or within the REGAL equipment itself. No speculation is made to identify this difference but it is felt that the magnitude is not large enough to indicate that there is any significant degradation in the REGAL system performance under dynamic conditions.

3.2.3.2 Dynamic Range Tests. - Initial testing of the REGAL Dynamic Range accuracy in the Fall of 1961, uncovered shortcomings in the method of data gathering. Originally, the REGAL range parameter was recorded by means of a galvonameter on the Minneapolis-Honeywell recorder. This recorder under the very best conditions provides an accuracy of one percent or .01 inch, whichever is greater. When using one channel with a

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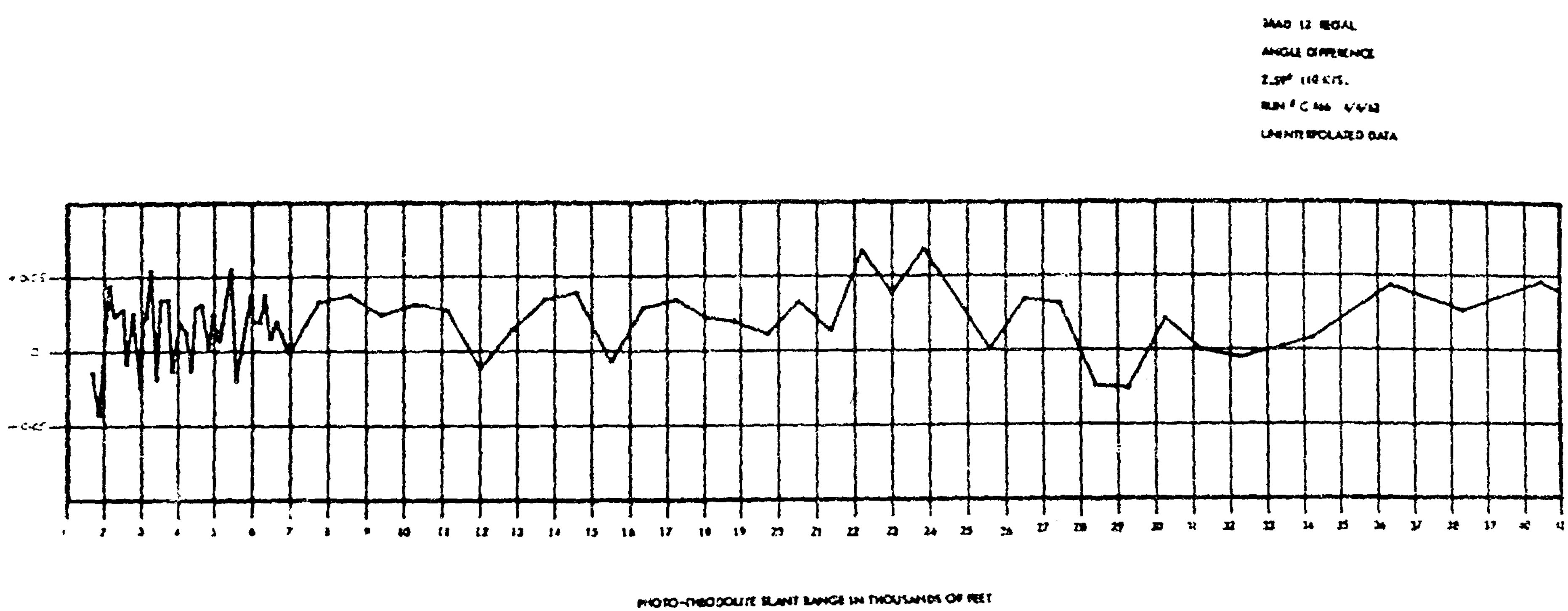

Figure 3-36. Typical Angle Recording

total deflection of 10 inches, this corresponds to a REGAL Dynamic Range accuracy of 600 feet at maximum range and 60 feet at minimum range. Even to achieve these accuracies, calibrations of the recording system were necessary immediately prior to and after a test run. In actual practice results appeared to be closer to .02 inch and two percent when everything involved with reading the data was considered. It was therefore decided to divide the total range coverage into three separate channels for the tests made in the Spring of 1962. The first area concerned REGAL's range from zero to approximately 7000 feet. With a deflection of ten inches this would correspond to an accuracy of 70 feet at 7000 feet and 7 feet at zero range. The second channel had a coverage out to 30,000 feet with a respective accuracy of one percent. The third channel had a range out to 60,000 feet with this same relative accuracy. Even when this method of recording was used, along with pre-flight calibrations of the recorder, there existed large discrepancies in reading the data. A typical example is shown in Figure 3-37. As shown, severe discrepancies exist where transfer is made from one channel to another. Also shown is a pre-calibration curve which illustrates that changes in offset and sensitivity of the medium and coarse channels occur during the flight. Consequently, a large portion of the data gathered during these tests is degraded by the basic instrumentation and these errors must be considered.

For the purpose of this report the tabular data was examined to determine if any appreciable degradation exists in the dynamic data with respect to the static results. The data was given close analysis because of the instrumentation's inaccuracy, and where possible, the data was used. Prior to each flight, bench calibrations and runway static calibration tests were performed. A typical bench calibration plot recorded prior to each flight is shown in Figure 3-38.

These static tests indicated a set-up error of 94 feet. The results of these static tests along with the dynamic results indicated very little degradation due to velocity. If better instrumentation accuracy were available, the amount could be specified. It appears the rms error is generally less than 25 feet. Shown below are several examples of corrected data from the fine data channel obtained from the NAFEC tabular data.

Flight #	Range Mean Error In Feet	Range Standard Deviation In Feet
410	+1.68	22.67
411	+44.78	77.01
418	+46.35	33.44
424	-12.81	27.78
431	-17.82	46.50
439	-65.93	21.64
449	+54.85	18.43
456	+35.94	10.59

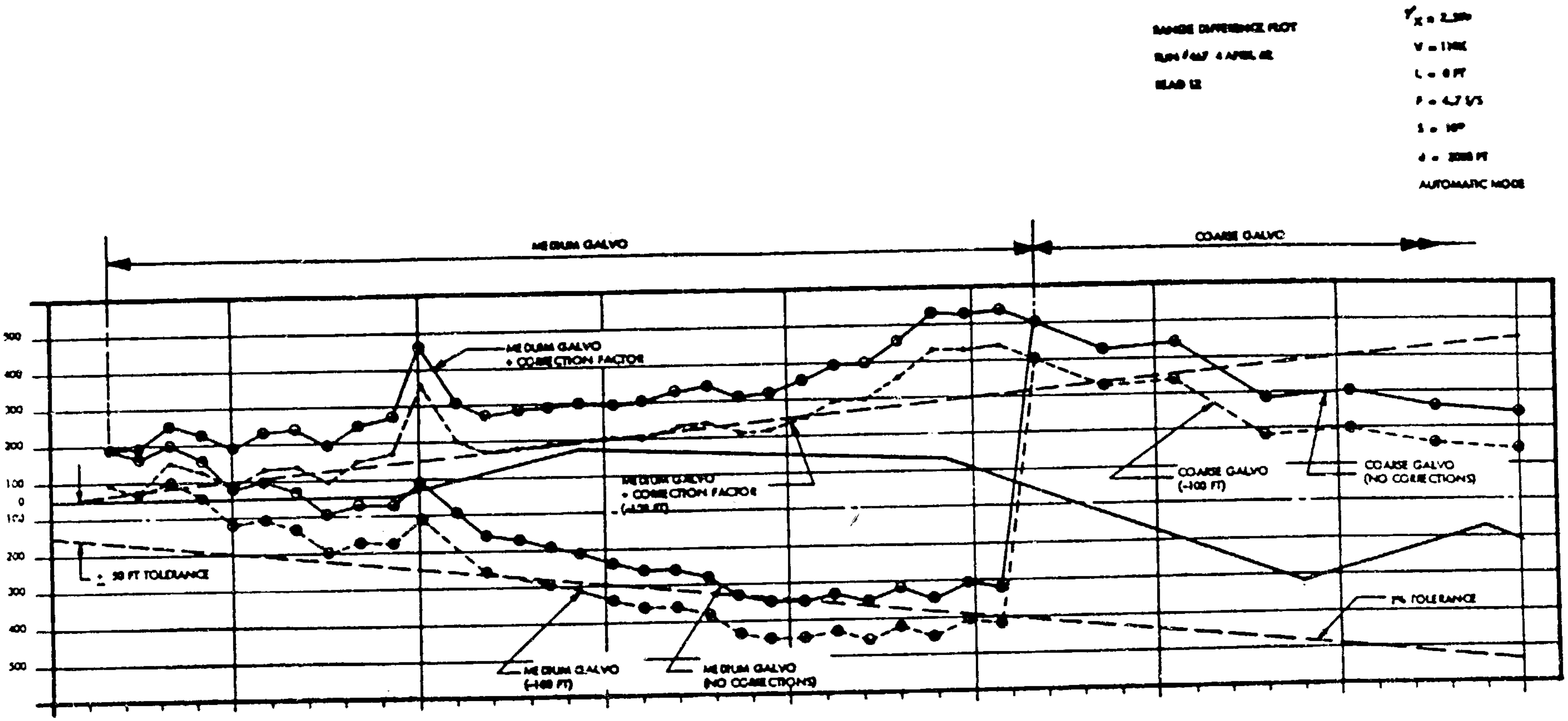

Figure 3-37. Typical Range Recording

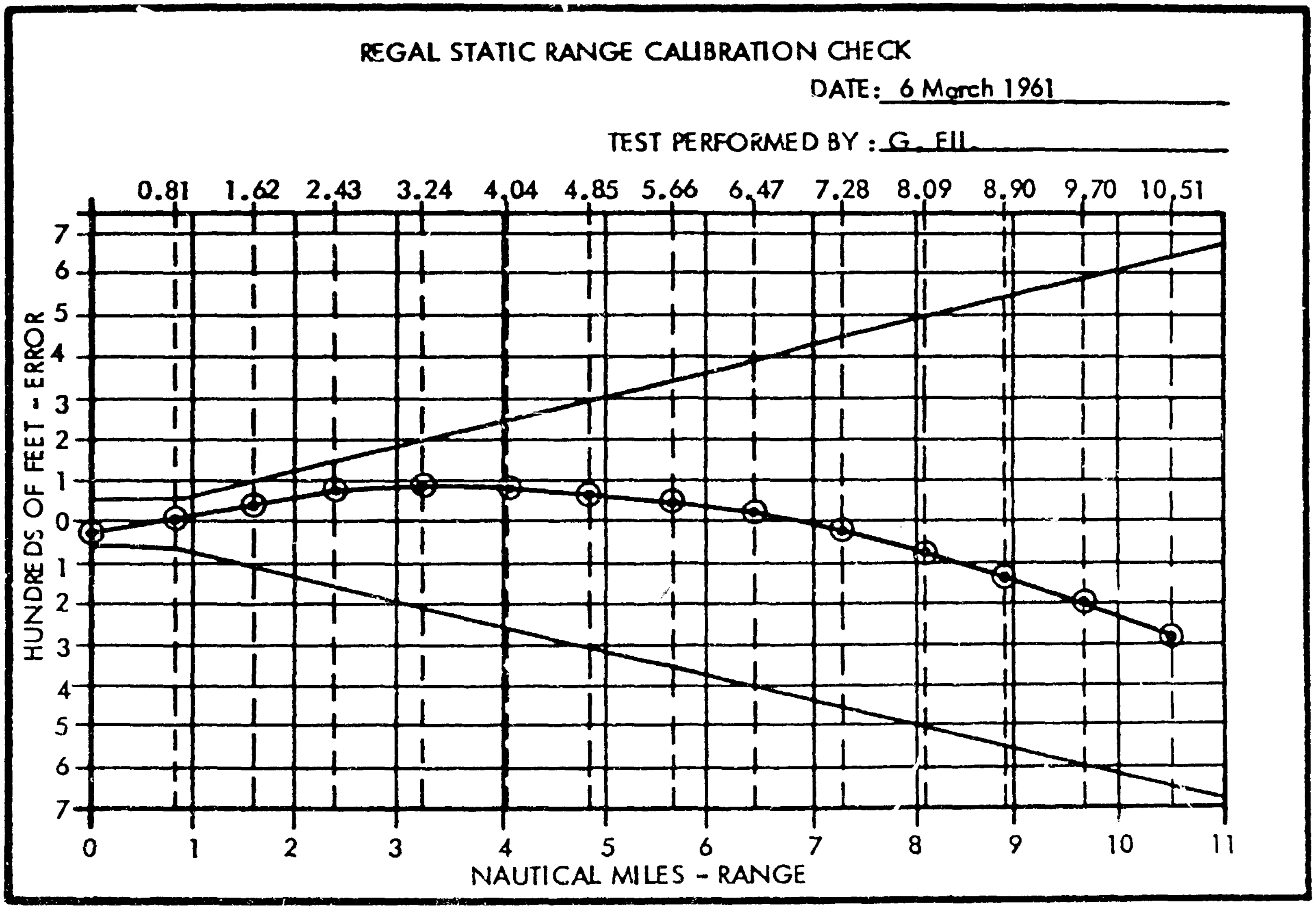

Figure 3-38. Typical Bench Calibration Plot

3.2.4 Flight Control Testing. - Evaluation of the REGAL system suitability for manual or automatic approach and landing was carried on intermittently starting in the fall of 1960 and continuing through the spring of 1963. The flight control testing effort included evaluation of the REGAL data quality, evaluation and optimization of the flight control equipment and checkout of the instrumentation, in addition to evaluation of the overall system performance. Hence a very large number of manual and automatic approaches were made on which there was no attempt to land automatically. In the course of this program, over 600 manual and automatic approaches were flown, and over 200 fully automatic landings completed.

3.2.4.1 C-54 Aircraft. - In the early parts of the program successful attempts were made to control the aircraft using REGAL from the maximum range to the inner marker. Various autopilot gains were adjusted to optimize control and minimize porpoising. The basic system guidance quality was judged equal to or better than the ILS glideslope. Most of the judgements made at this time were with respect to ILS and strictly from a qualitative viewpoint.

As the program progressed, attempts were made to fly with REGAL guidance closer to the specific aim point. Although good stability was achievable from the outer marker to beginning of flare, it was felt that the terminal stability was affected by noise on the REGAL data. It was decided to incorporate a scan-to-scan averager at this time which greatly improved the basic REGAL data quality. To obtain further control stability, the sensitivity of the REGAL data was course softened as a function of range during the latter part of the approach. These improvements assured the aircraft's delivery to the beginning of the flare zone with minimum errors being experienced.

Starting in the winter of 1962, successful landings were performed on this aircraft with limited instrumentation. During these landings, further optimization of the landing system parameters was performed. From this time on, the only adjustment that was performed was an altitude offset correction which required occasional adjustment. In all cases when this was needed it was noted on the recorded data. During the actual testing period in the spring of 1962, complete airborne and ground instrumentation was used. More than 60 fully automatic touchdowns were made in the C-54 aircraft with different parameters in the flareout computations. As of July 2, 1962, a total of 35 landings were categorized as good for which recorded data was available. There were two series of complete landings made on successive attempts (thirteen in one case and twenty in another). The quality of these landings was judged to be from good to excellent by the aircraft crew. On the runs that culminated in a complete landing where no altitude offset was adjusted, the longitudinal dispersion was well within the ±500 touchdown zone. Ground observations indicate the one sigma longitudinal dispersion is in the order of 150 feet.

One major parameter which definitely contributed to non-successful landings was airspeed. On most attempts to land when the airspeed was more than five knots over the desired value, manual takeover by the pilot was necessary.

Unfortunately a very limited amount of reduced data is available and a more detailed analysis cannot be performed.

3.2.4.2 C-131 Aircraft. - During a two week interval in December 1961, there was a limited amount of testing involving this aircraft. This period was primarily devoted to setup and checkout of the airborne computer and REGAL for manual approaches. Approximately 50 manual approaches were performed under various conditions of equipment adjustment. A series of 13 were successfully flown manually through flare to touchdown. Because of the very limited amount of instrumentation, an insignificant amount of recorded data was available for reduction. Aircraft crews comment were that, considering what was accomplished, the results appeared very encouraging. Unfortunately no further use of the aircraft was made on the program. This was because the aircraft being assigned to other Air Force programs and a lack of funding for a more operational autopilot.

3.2.4.3 Aero commander Aircraft. - A relatively large amount of flight testing, both manual and automatic was performed using the Aerocommander aircraft. In the first series of attempts to land, problems appeared concerning the Lear/Sierra computer. Although landings were accomplished there was inconsistent porpoising in the terminal flare zone. These oscillations in the flare trajectory caused a large number of landing attempts to abort. Investigations performed by the Lear personnel indicated that the servo systems in the computer were experiencing reliability problems. Consequently it was decided to perform modifications on the computer at the Lear facility in Santa Monica, California. On the return of the modified computer to NAFEC, further laboratory bench testing indicated that the problem had not been completely corrected, but it was decided that further flight tests would be performed anyway. As indicated, the problems were still prevalent and after a considerable amount of flight testing with limited results, it was decided to terminate this portion of the program.

Although the flare computer portion of the system failed to achieve the desired performance, the results were not completely void. More than 100 completely automatic approaches were performed with excellent results. More than 65 automatic landings were made with this aircraft.

On at least 40 complete flights which culminated in touchdown where reasonable flare trajections were generated in the computer, the Lear L-5 autopilot performed adequately. Therefore these tests do indicate the capibility of a conventional autopilot to be used in a complete landing system for a relatively light aircraft.

During the flight tests and ground checkout on the Aero Commander aircraft, it was observed that the low angle coverage of the REGAL data was not as good as measured in the static tests. There were enough observations in this aircraft and rechecks of the static data to conclude that this phenomena was not due to a partial failure or misadjustment of the equipment. The degraded low angle coverage seemed to be more severe when the aircraft antenna installation resulted in the presence of reflections from the nose of the aircraft which accentuated the ground reflected signals.

Recommendations were made for moving the aircraft antenna either higher or further forward, but this could not be included in the program schedule and no investigation was made into the cause of the above described phenomena.

3.2.4.4 Bendix B25 System. - This aircraft participated in the REGAL program during 1960 and 1961 as a part of an Air Force landing system study program being performed by Bendix Corporation. The primary purpose was to investigate various computer techniques being considered for use with scanning beam systems.

In 1962 and 1963 this aircraft was used to perform a side by side comparison of the Flarescan and REGAL systems. Both the airborne computer systems used ILS glideslope for the approach phase so that the biangular Flarescan techniques could be evaluated on a comparative basis.

To accommodate the B25 test program, it became necessary to relocate the REGAL ground facility. This new location was approximately 1200 feet to the rear of the original site. The reason for this new location was to provide an adequate coverage in the flareout and touchdown regions with the REGAL equipment so that the B25 aircraft could make use of the ILS glideslope equipment for the approach phase. Initial testing during November, 1962 at this new site indicated that the minimum coverage was degraded below ten feet.

An examination of the new site ground terrain and review of the test data was then performed by Gilfillan personnel. The examination revealed that the elevation scan axis was 8 feet above the mean ground plane rather than the recommended 9. 5 foot position above the mean ground plane as specified in the REGAL final engineering report. The test data appeared to be clouded by ambiguities caused by the data gathering techniques due to no sign reversal of angles below zero degrees and inclusion of erroneous zero angle readings in the data. After collating the data, it was still determined that the low angular coverage was degraded. This was expected once it became known that the elevation angle axis was misplaced with respect to the mean ground plane. To correct this, Gilfillan personnel recommended that the antenna be raised at least 18 inches.

This was accomplished and data gathered in May, 1963, indicated that at a height of 24 inches the low angular data had been significantly improved. A series of test runs were reduced and the results of coverage are shown in Figure 3-39. A typical linearity plot of the touchdown point is presented in Figure 3-40. The angular data was within the specified system accuracy of 0. 05 degree down to angles in the order of 0. 25 degree over ranges from 700 to 2300 feet.

This additional test did verify the theory presented in the Final Engineering Report that there is an optimum altitude above the mean ground plane for location of the antenna scan axis.

Flareout for the REGAL system started at approximately 65 feet. After more than 60 landings with the biangular flareout techniques, it was concluded that the use of the REGAL DME was preferred.

Although the results of these landing tests are presently not available, it is known that over 100 complete landings to touchdown were achieved with consistent results. The ability of REGAL to provide range data presentations to the pilot was shown to be desirable. The Bendix tape dial unit displayed range-to-go, altitude, and altitude rate all of which depend on the REGAL range parameters. This instrument appeared to give the pilot a high confidence level that the system was operating correctly.

3. 2. Miscellaneous Test Results

3. 2. 5. 1 Scan-to-Scan Averager. - The REGAL ground system uses two antennas which alternately scan the approach airspace. Because of the physical separation, there is a difference in the transmission path and in the phasing of the ground refelcted energy. Consequently, the signals as received

MINIMUM REGAL ALTITUDE
COVERAGE AT NEW SITE ON RUNWAY 13-31
HEIGHT OF ANTENNA SCAN AXIS
10.5 FOOT ABOVE MEAN GROUND PLANE
(24 INCHES ABOVE ACTUAL GROUND SURFACE)

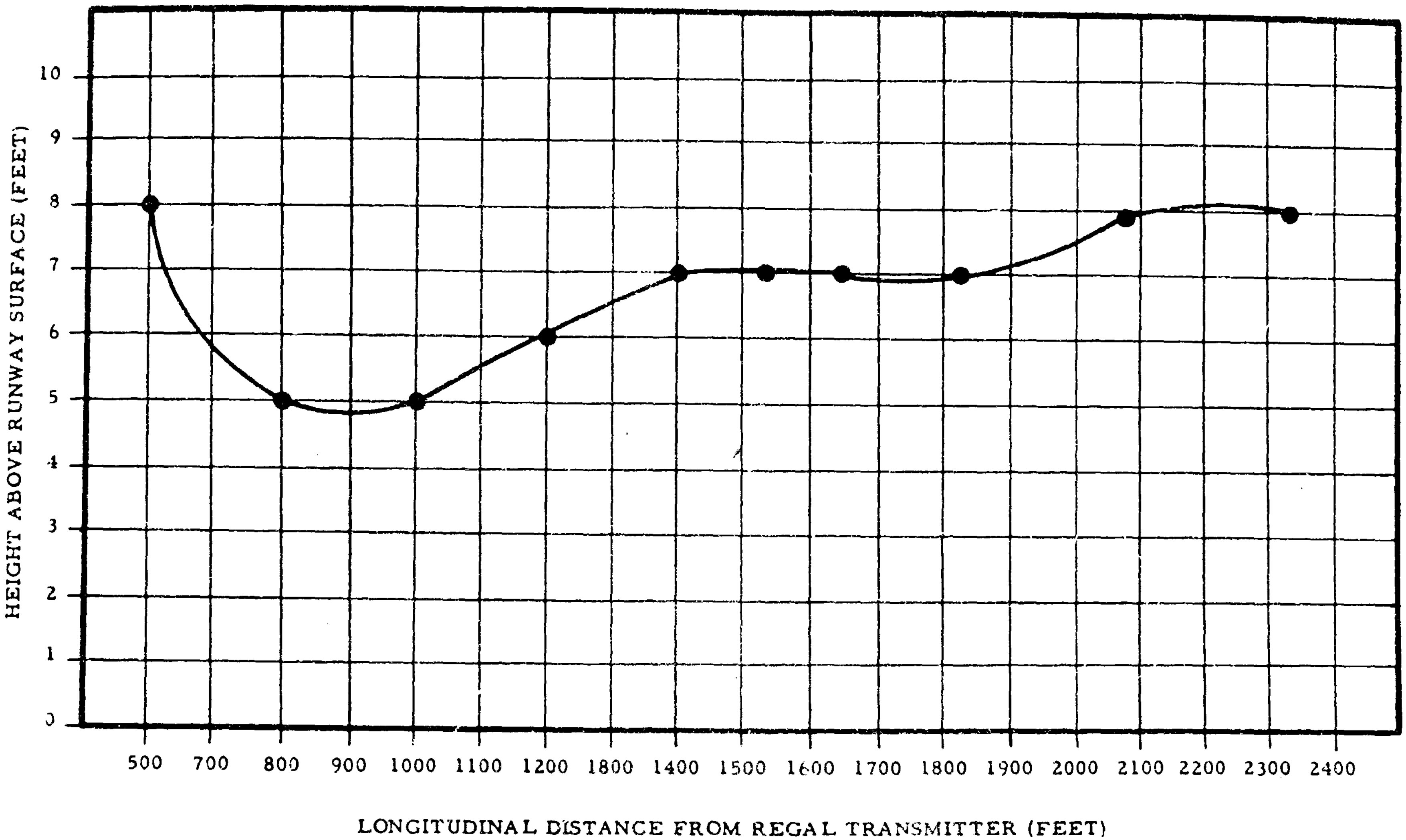

Figure 3-39.

ELEVATION ANGLE ERROR
NEW REGAL SITE
SITE 120
RUNWAY CENTERLINE
ANTENNA BASE HEIGHT 24 INCHES

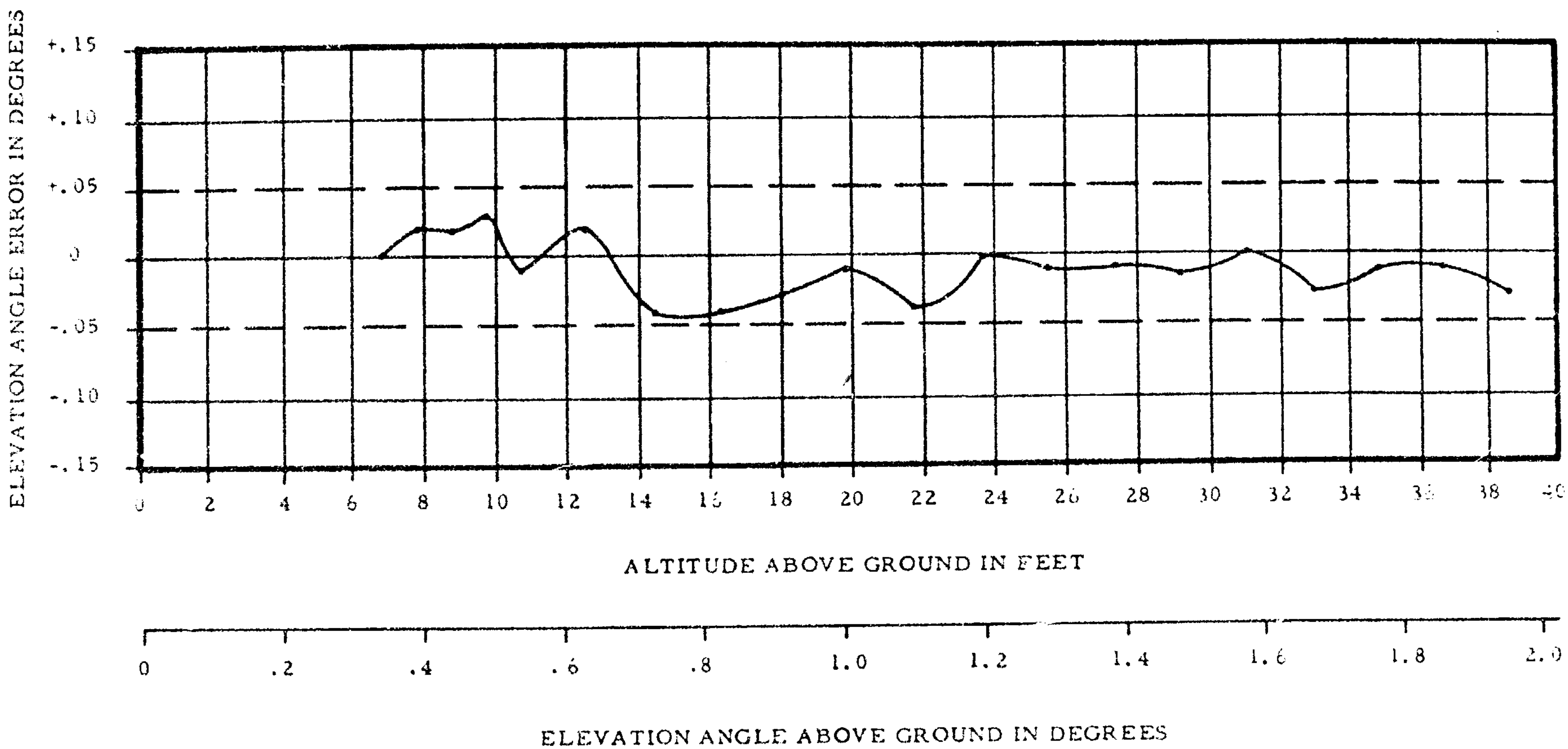

Figure 3-40.

by the airborne receiver change by minor amounts causing a scan-to-scan difference in the readings from the REGAL angle output. This scan-to-scan variation in angle caused small problems when used for automatic control of an aircraft using an autopilot. To alleviate this problem, Gilfillan fabricated a scan-to-scan averager unit which selectively stores the previous angle reading and provides the average of two sequential scans as an output. When the unit is used with a basic REGAL scan rate of five samples a second, the delay incorporated in the output signal from the unit is no greater than 100 milliseconds. This time delay does not cause problems under a closed loop condition and enhanced the signal quality considerably. Figure 3-41 contains a typical recording which was gathered using the FAA C-54 aircraft at NAFEC in Atlantic City, New Jersey. Both the input and outputs of the averager are shown. It can be seen that the total amount of scan-to-scan signal noise is reduced considerably.

Although this scan-to-scan error appears to be undesirable, the basic frequency was high enough such that the autopilot system was not significantly affected. In some ways this scan-to-scan difference offered more accurate position determination when two successive scans were averaged. The system resolution of 0.020 contributed to the problem of scan-to-scan noise. It is therefore concluded that any future system design should use a resolution between 0.005° and 0.015°.

3.2.6 Reliability. - The original objective of the REGAL program was to determine feasibility of a scanning beam interferometer antenna system to provide air derived space position data down to low elevation angles. Before considering reliability as a pertinent area, it should first be recognized that the REGAL hardware now at NAFEC was fabricated during a development program that was relatively short. The adaptation of existing known designs from other systems was used as an expedient solution to minimize price and provide prompt delivery. Feasibility being the primary goal, the original design criteria for total equipment life was 200 hours with little emphasis being given to high reliability. Had Gilfillan known in the beginning that this equipment would be expected to perform continuously for periods approaching 3000 hours with low failure rates, the design approach from a reliability viewpoint would have been quite different.

During the evaluation period when it became known that a particular small problem area could have been corrected by means of a modification, this was discouraged for fear of invalidating previously recorded data. Later in the program, Gilfillan proposed a group of modifications to the REGAL equipment. After a very careful consideration of the modification program price, the modification time scale and the short test program planned at that

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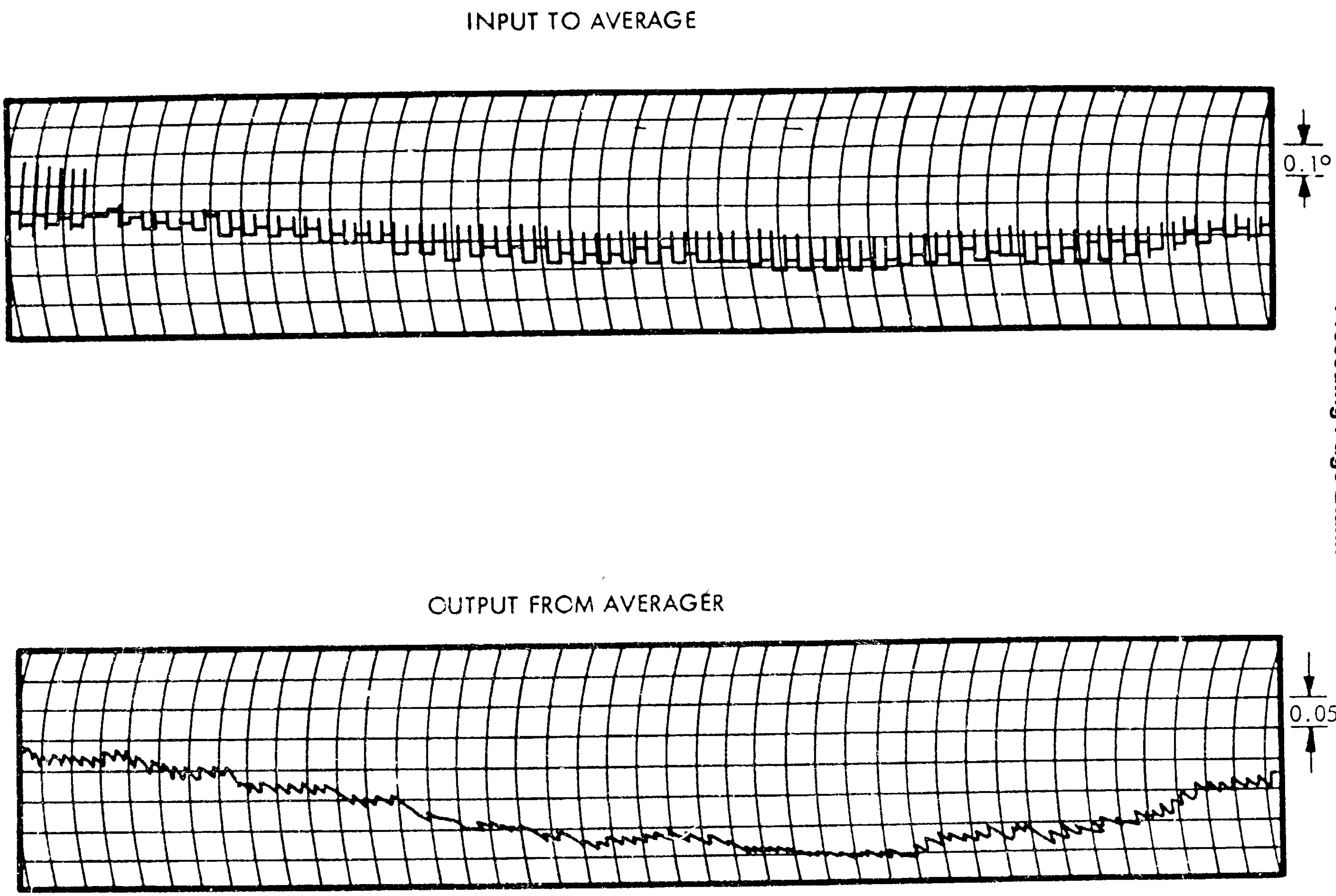

Figure 3-41. Typical Scan-To-Scan Ratio

time, Gilfillan felt compelled to recommend that this money be used for enhancing the quality of a new second generation system rather than gaining just a small amount of reliability in the original system. In considering all this and examining the records, it appears that even under the conditions that prevailed, the REGAL equipment has demonstrated that the major elements essential to the REGAL concept have a higher reliability than expected.

3.2.6.1 Ground System Antenna Scanner. - Originally, it was felt that the REGAL antenna scanning rate of five scans per second would definitely impose a limited life expectance on the scanner. Throughout the program the actual problems dealing directly with the antenna scanning mechanism was quite low. Only on one occasion was it necessary to replace the main trunnion bearings on one antenna boom and this was after it was determined that the lock-nut had worked loose causing excessive play in the bearings. However, no substatntial evidence of wear existed other than that caused due to removal methods, but it was decided to replace these bearings with new ones. For the remainder of the testing program the only maintenance that was needed was periodic injection of grease. Actually, at least 2500 actual running hours of service was provided with no mechanical failures being registered. One area concerning the Antenna Scanner system were the problems experienced with the data take-off units.

The data take-off problem was primarily due to a sagging of the scale illuminator lamp filament which caused the light filament to be removed from the center of illumination of the associated optical system. To correct this, either the lamp holder required readjustment or lamp intensity had to be raised by means of the voltage control. This problem can be easily corrected in future systems by mounting the lamp in a vertical position.

3.2.6.2 Ground Transmitter and Modulator. - These units were adapted from existing designs and the duty cycle requirements for REGAL were considerably higher. It was felt that the original units were adequately overrated in design and could easily handle the proposed increase. Unfortunately, this was not the case and problems were experienced.

This problem concerned the pulse width in the ground equipment modulator. The modulator's keyer tubes, as they aged, caused changes in output pulse shapes which required occasional adjustment to the input triggers to maintain a proper output pulse width. This problem can be easily corrected in future systems by designing for a larger margin of safety on the modulator duty cycle. When the equipment was first delivered to NAFEC it was necessary to replace these tubes quite often. In evaluating the problems it was determined that the interlocks involved with the high voltage was not providing suitable protection to the control and screen grids of these tubes. After correcting the interlock wiring, the tube life was increased significantly.

Another small problem involved replacement of the rectifier tubes in the low voltage power supply. This problem can be solved in future designs by incorporating solid state rectifiers which inherently have a higher reliability.

3.2.6.3 REGAL Receivers. - The greatest area of concern dealing with REGAL's reliability was the receivers. It should be emphasized that this was an attempt to design a solid state receiver which was minimum in weight and size with long time reliability not being a primary goal. Certain sections of the receiver exhibited outstanding reliability where other areas fell short of a reasonable goal. During the static and dynamic test periods, it was shown that under a "hands off" condition, three REGAL receivers displayed very good reliability. Of all the areas under concern, two sections of the receiver should have extra consideration in any future equipment designs.

The first involves the DME transmitter magnetron. Many of the problems experienced with this tube involved high line voltage on the 400 cps power. The manufacturer's specification on this tube requires the filament voltage to be contained within ±2% of the nominal value. During the first portion of the program an alarmingly high failure of this tube was definitely caused by high line voltage. This was eventually corrected after the installation of solid state inverters as REGAL power sources in the aircraft. This substantially increased the life of this tube. Even with this improvement, it still would be desirable to provide future units with greater reliability. Consideration should be given to power klystrons or traveling wave tubes for this application.

The second area of concern was the receiver video amplifier and AGC sections. Primarily the problems experienced manifested themselves as requirements for AGC adjustments. The adjustments were generally required to compensate for degradation of the transistors in the video amplifier. There are vastly improved transistor types available today which could enhance the design of future systems reliability. For future designs, it is recommended to possibly change the receiver type to a superhetrodyne. This can provide a greater range coverage capability at a reduced transmitter power in addition to better receiver performance.

4. CONCLUSIONS

4.1 System Accuracy

The following conclusions are drawn from the static ..d dynamic evaluation of the basic REGAL System performance.

a. The Angle data accuracy is in the order of 0.030 degrees rms
b. The Range data accuracy is in the order of 50 feet rms, or 1 per cent of range
c. The minimum angle coverage of the angle data is 0.25° above the ground plane. This corresponds to an aircraft antenna height of less than 6 feet at the touchdown point
d. The Angle data coverage is from 700 feet to more than 15 miles in range and more than ±20 degrees in aximuth
e. The Range data coverage exceeds the Angle data coverage except where a saturation limit designed into the airborne receiver limits the maximum useful range to approximately 8.5 miles
f. The Angle data stability is excellent
g. The Range data stability is marginal within the specification for landing aircraft, but is acceptable

4.2 Landing System Performance

The following conclusions are drawn from the flight testing of the REGAL System operating in conjunction with the several flight control systems.

a. The REGAL guidance system has been demonstrated to be relatively suitable for automatic landing by completion of approximately 200 automatic touchdowns.
b. No measure of touchdown dispersion or sink rate can be given, however, the quality and repeatability of the landings was promising.
c. The DME ranging technique is very desirable for course softening of central signals computation of altitude for flareout control and operation of range and altitude pilot displays.

d. The fixed path flareout computer may possibly be adequate for landing under conditions of tail winds of 15 knots or more.
e. The data rate of five samples per second is suitably above the minimum acceptable.
f. The data noise of the basic REGAL equipment in the order of 0.02^{o} to 0.03^{o} rms is marginally acceptable and is reduced to a very acceptable level by scan-to-scan averages.

4.3 Systems Configuration

The following conclusions drawn from the general performance of the system are applicable to future system design.

a. The linear array antenna scanned by a simple mechanical drive has proven to be good.
b. The use of the interferometer antenna patterns has provided very good low angle coverage
c. The use of digital data transmission has proven very reliable and stable.
d. The transmitter-modulator has shown poor reliability.
e. The airborne receiver AGC has suitable performance but is difficult to adjust.
f. The airborne range tracker has marginally acceptable performance and reliability, and requires specialized equipment and procedures for alignment.
g. The "Data good circuits" have performed well and demonstrate a desirable concept.
h. The system should have finer data resolution.
i. Meaningful tests of a system such as REGAL, under dynamic conditions, requires theodolites and recorders substantially more precise and better integrated than those used.

4.4 Summation

The REGAL System has successfully demonstrated a technique for obtaining precision position information at the low altitudes associated with aircraft landing. The flight testing has demonstrated the system suitability for controlling automatic landings in addition to the extra advantages of precise range data. The REGAL System has thus fullilled the objectives of the experimental program and has formed a sound basis for further development of an automatic landing system.

APPENDIX A

SURVEYORS DATA FOR ORIGINAL REGAL SITE

	DISTANCE FROM REGAL		
SITE	X IN FEET	Y IN FEET	H*
20*	700.06	206.21	69.842
21*	1200.06	206.21	71.279
22*	1700.06	206.21	72.633
22**	2200.06	206.21	73.987
24A	2200.06	281.21	75.100
24B	1950.06	281.21	74.461
25	1700.06	281.21	73.704
25A	1450.06	281.21	73.106
26	1200.06	281.21	72.213
26A	950.06	281.21	71.628
27	700.06	281.21	70.808
30*	700.06.	356.21	69.799
31*	1200.06	356.21	71.225
32*	1700.06	356.21	72.656
32A*	2200.06	356.21	73.979

* READINGS IN ALTITUDE WITH RESPECT TO M. S. L.
ALTITUDE OF REGAL SITE = 68.459