FINAL ENGINEERING REPORT

FOR AN

EXPERIMENTAL ELEVATION POSITION-DETERMINING SYSTEM FOR LANDING

This report covers the period 1 January 1959 to 30 May 1960

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FEDERAL AVIATION AGENCY
Contract No. FAA/BRD-54

30 June 1960

ABSTRACT

This final report presents the technical data derived during the development program for an experimental elevation position-determining system for aircraft landing control. This program has been assigned the code name REGAL (Range and Elevation Guidance for Approach and Landing). The development of the REGAL system was performed under the Federal Aviation Agency contract FAA/BRD-54 during the period 1 January 1959 through 30 May 1960.

The REGAL system operates on the principle of air-derived position data and provides the aircraft with polar-coordinate position (elevation angle and range) information in the elevation plane, referenced to a ground transmitter. With this information, the appropriate control maneuvers may be determined for an optimum approach and landing.

This report presents the results of, and conclusions from, the design effort and preliminary field testing, with the contractor's conclusions concerning the problem areas.

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PART I

1. PURPOSE

The Federal Aviation Agency (FAA) is developing an advanced approach and landing system under its new Equipment Development Program (Phase III). This program will develop an all-weather aircraft landing system sufficiently flexible and accurate to provide all types of present and future aircraft with guidance during approach, landing, and rollout.

One model of an experimental elevation position-determining system for aircraft landing control has been developed under the Federal Aviation Agency Contract FAA/BRD-54 during the period of 1 January 1959 through 30 May 1960. This program has been assigned the code name REGAL (Range and Elevation Guidance for Approach and Landing).

The primary purpose of the REGAL system development has been to solve the problems associated with the vertical guidance portion of an automatic landing system. There were two main design objectives for the system:

a. To demonstrate a solution that overcomes the low-altitude limitations of present-day approach systems, which are caused by the degradation of position information resulting from the ground reflections associated with low-angle, radio magnetic energy propagation.

b. To provide a tool that is useful in investigating the dynamic factors associated with the flight control of an aircraft during the landing maneuver.

The REGAL system has been installed at the FAA National Aviation Facilities Experimental Center in Atlantic City, New Jersey for thorough testing with respect to the accuracy of position information provided to an aircraft during the approach and landing maneuver. The REGAL system will also be used to investigate several different flight path computation and control systems that have been fabricated by other companies and installed in various aircraft.

1.1 Purpose of Report

This final report presents the technical data derived during the development program for an experimental elevation position-determining system for aircraft landing control. This program has been assigned the code name REGAL (Range and Elevation Guidance for Approach and Landing). The development of the REGAL system was performed under the Federal Aviation Agency contract FAA/BRD-54 during the period of 1 January 1959 through 30 May 1960.

A description of the system principles is presented in this report together with a brief description of the equipment on a block diagram level. Since engineering level instruction manuals have been prepared that fully describe the equipment and the theory of operation, this report does not offer complete coverage of these areas.

This report presents a condensation of the more important technical data obtained during the development of the Experimental Elevation Position-Determining System for Landing (REGAL equipment). This data is presented as background material to assist in the evaluation and testing of the REGAL Equipment and to aid in the establishment of future automatic landing system concepts. It contains a series of preliminary test results and technical comments, and a discussion of ancillary technical effort undertaken during the design program.

2. GENERAL FACTUAL DATA

This section contains a general description of the REGAL system, an enumeration of its major advantages and the special techniques employed. Also included is a summary of the engineering effort expended in the program, applicable patents, and reference data.

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 determine its 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 very definite advantages over a system wherein a radar equipment on the ground determines each aircraft's position, calculates guidance commands, and telemeters these to the appropriate aircraft. Some of the advantages 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, both 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 receiver, the necessary demodulation equipment to extract position data, and a flight-path control computer. The system uses a simple one-way transmission of electromagnetic energy which results in additional technical advantages, as follows:

a. One-way transmission of angle data results in improved range performance (greater than 10 miles).

b. Radar scintillation is non-existent -- 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-coordinate position (elevation angle and range) information in the elevation plane, referenced to a ground transmitter that is sited just beyond the touch-down point and adjacent to the runway.

To define completely the aircraft's position with a third data coordinate, azimuth angle information will, in the future, be provided referenced to a second equipment 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 rapidly 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 precise measurement of the elevation of the aircraft with respect to the ground equipment.

Although systems as described above have been proposed in the past, this approach to an automatic landing system has not heretofore been exploited, because there still remained a serious problem of providing accurate data close to the ground in the touchdown region, where the accuracy requirements are the most severe. The present REGAL system incorporates several unique features which overcome the technical problems of providing the data necessary for automatic approach and landing.

One problem, which has limited many other systems, is the deterioration of electromagnetic position information due to ground reflections. The REGAL ground equipment overcomes this limitation by employing a narrow-beam antenna which scans in a downward direction only. This feature insures that the antenna beam will always pass through the aircraft before it strikes the ground. The airborne detector can readily discriminate against ground-reflected data by accepting only the first-received information in each scan cycle.

Additional techniques enable the REGAL system to obtain a very high order of accuracy at critical short ranges and low altitudes. One such technique is the use of an antenna pattern with a sharp center-null. At close ranges (in the Fresnel region) where the beam of a conventional antenna is severely defocused, the null in the REGAL antenna pattern is still well defined. This technique 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 deg.

The REGAL equipment includes an air-to-ground DME-type ranging system which interrogates the ground equipment immediately following receipt of angle data. A range reply, which is interlaced between the angle data, is transmitted from the ground to the airborne receiving equipment. Accuracy of the range measuring system will be approximately 1 per cent of range.

2.2 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 only. The equipment was designed for the objectives of the immediate program. It was designed to meet the particular specifications for an experimental equipment rather than optimum specifications for a final landing system. Design was also directed toward equipment which would have a limited life and reliability capability and which could be available for the flight test program at an early date.

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

2.2.1 REGAL Transmitting Set. - The REGAL Transmitting Set (ground equipment) generates a radiation field over a large area with coded transmission signals, enabling all aircraft within its coverage to determine their elevation position with the high degree of reliability necessary to accomplish their landing maneuver. The REGAL ground equipment (Figure 2-1) consists of an antenna system, which includes the scanning drive mechanism and data take-off units; and a modulator group, which includes a pulse coder, a multiple-pulse X-band transmitter, and a receiver.

A functional block diagram of the REGAL Transmitting Set is shown in Figure 2-2. Angle signals are generated in two data take-off units, one for each antenna. Each of two data take-off units consists of a two-channel preamplifier and two photo-cells which are mounted in a container on the antenna pedestal.

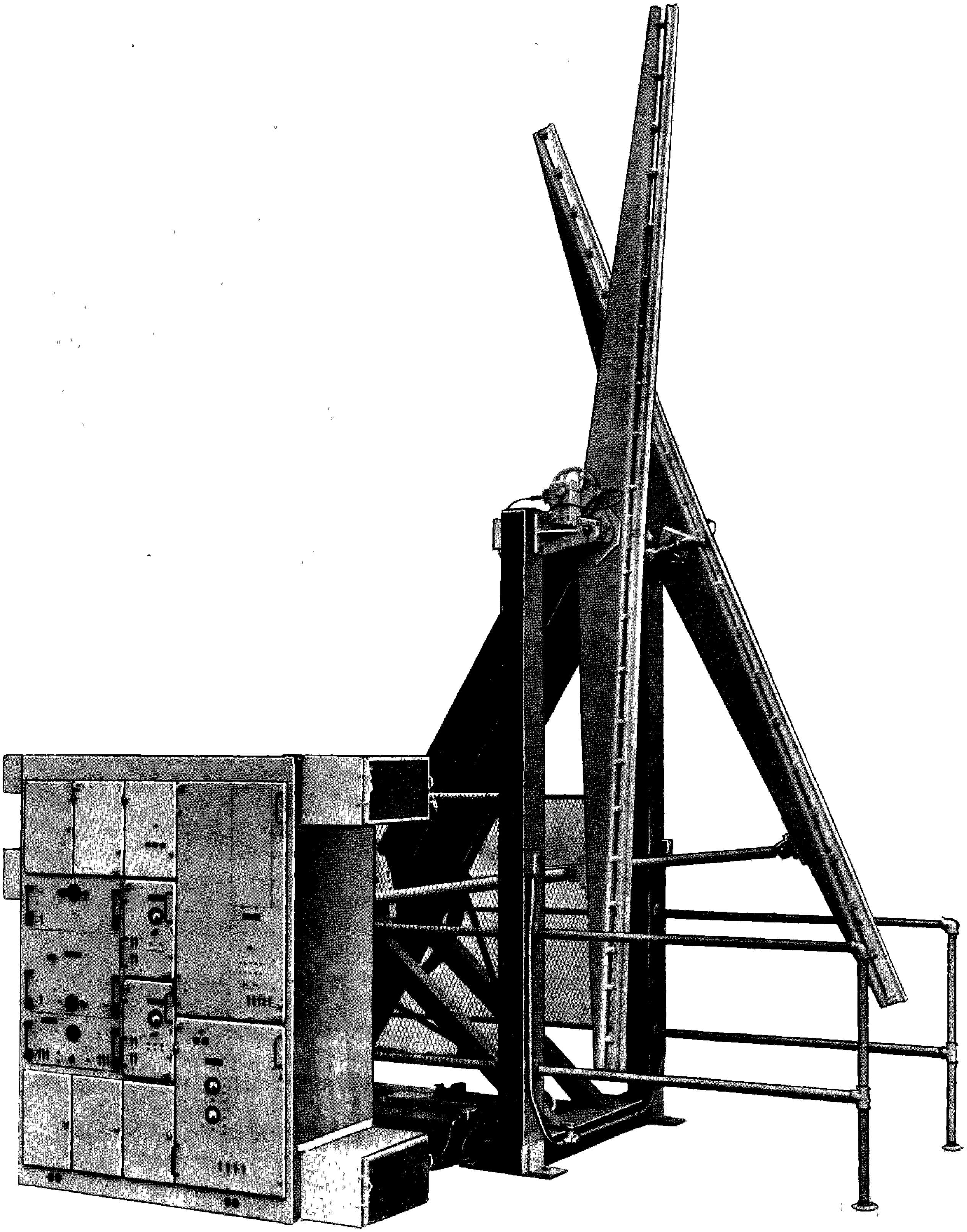

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Figure 2-1. REGAL Transmitting Set

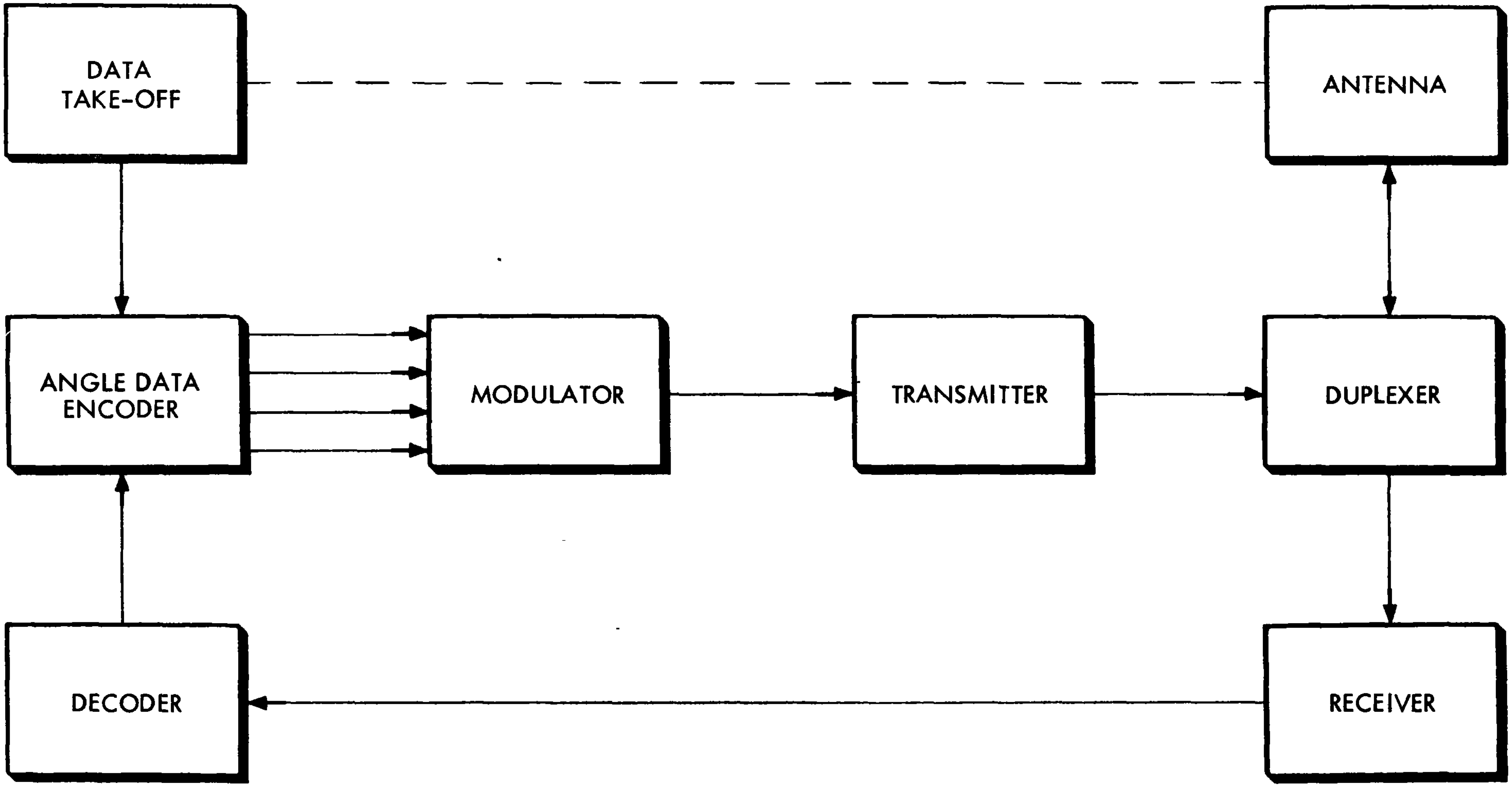

Figure 2-2. REGAL Transmitting Set Block Diagram

Light from a source in each container is focused through a prism and a lens to a graduated scale on the antenna. This scale on each antenna indicates the antenna angular position within a 20.8-degree sector. The scale is laterally divided into a coarse-data section and a fine-data section, with coarse and fine increments etched on the scale. On each data-takeoff unit, one of the two photo-cells is presented with an image of the coarse-data section of the scale and the other photo-cell is imaged on the fine-data section. When the antenna is scanning, the illuminated images of the etched scales pass over the coarse-data and fine-data photo diodes. The signals produced from the light modulation are amplified and standardized in the preamplifier and sent to the data encoder to be time spaced into angle-data codes.

The coded pulses from the data encoder are amplified and shaped in the modulator. The modulator delivers the output pulses through a 50-ohm coaxial delay line to the magnetron. The r-f output energy from the magnetron is transmitted through the duplexer to the r-f switch, which diverts the r-f energy alternately to the two time-shared antenna arrays.

The range interrogation signals received from an aircraft are routed through the duplexer to the receiver for amplification and are sent to the encoder for decoding. The decoded range pulses are mixed with the angle data and are applied to the transmitter to form a range reply.

2.2.2 REGAL Transmitter Characteristics. - The detail design specifications for 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:	
Scan (down-scan only)	+20.0° to -0.80°
Scan speed	5 scans per second
Scan time (active)	120 ms
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

FEATURE	CHARACTERISTIC
Receiver System Characteristics:	
IF bandwidth	15 mc
Sensitivity	-85 dbm for decoding of pair of 0.25-usec pulses spaced 0.9 usec

2.2.3 REGAL Receiver-Converter Group. - The REGAL Receiver-Converter Group (airborne equipment) consists of a receiver, decoder, digital-to-analog converter, range tracker, and a transmitter. This equipment (shown in Figure 2-3) 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 receiver-converter 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. (Refer to the REGAL Receiver-Converter Group handbook for more detailed information.) A functional block diagram of the REGAL Receiver-Converter Group is shown in Figure 2-4.

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

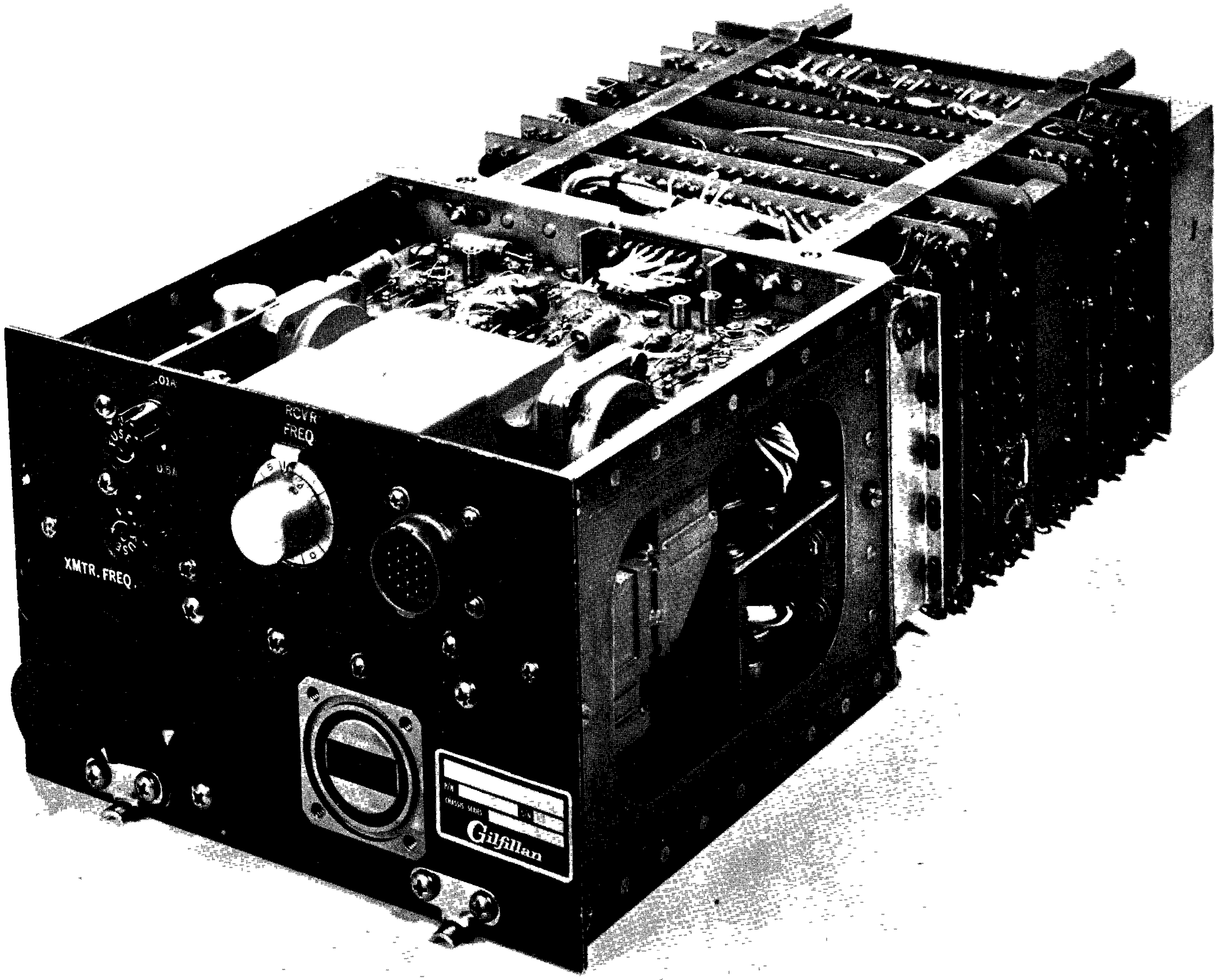

Figure 2-3. REGAL Receiver-Converter Group

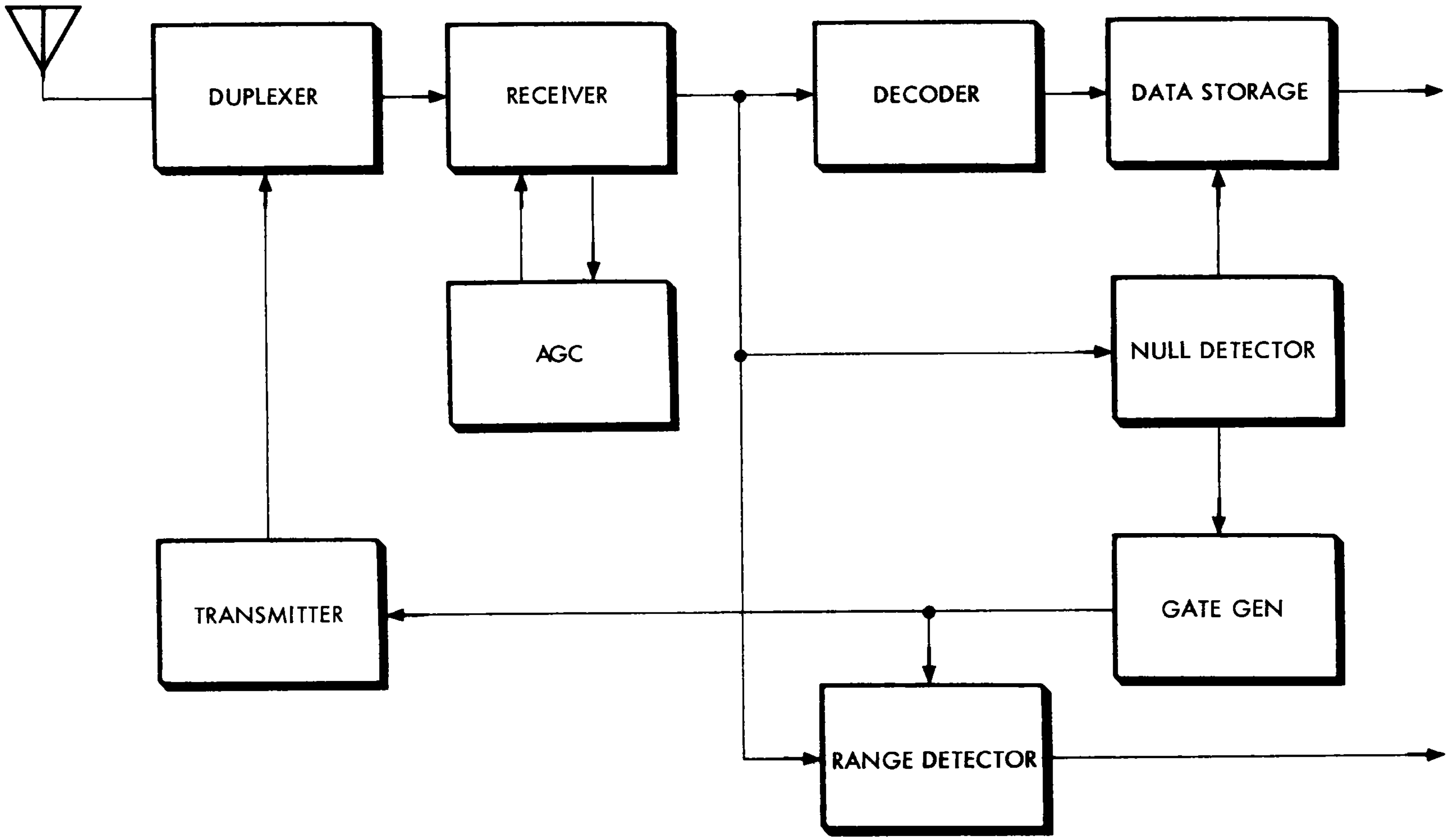

Figure 2-4. REGAL Receiver Converter-Group Block Diagram

the digital-to-analog converter (data storage) and converted to an analog voltage for readout by means of meter displays.

The video is sampled from the video amplifier and sent to the AGC amplifier where it is stretched, integrated, and fed back to the detector as a bias voltage. The bias voltage is used to regulate the amplitude of the incoming signal.

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. Range replies from the ground are received and fed to the range tracking system where the time delay is measured and converted to an analog voltage, which operates the DME meter in the aircraft.

Not included in the block diagram (Figure 2-4), is a power supply, which supplies the necessary voltages to the transmitter and receiver system.

2.2.4 REGAL Receiver-Converter Characteristics. - Specifications for Receiver-Transmitter include:

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

Specifications for the Data Converter include:

FEATURE	CHARACTERISTIC
Input signal:	
a. Coarse data	7-pulse code group (6 bit pcm)
Conditions for decoding	Only one pulse present in position prescribed for each bit
b. Fine data	2-pulse code groups 0.6 usec spacing
c. Range data reply	Signal pulse synchronous with interrogation

FEATURE	CHARACTERISTIC
Output signal:	
a. Elevation angle data	Analog voltage
Scale factor	0.90v/degree
Range	+20° to 0.8°
Accuracy	0.025° rms
b. Range data	Analog voltage
Scale factor	1.80v/n mi
Range	500 ft to 10 mi
Accuracy	50 ft plus 1% range
c. Range interrogation	
Pulses (PRF)	4,000 pulses/sec (approx.)

2.3 References

1. Preliminary Handbook of Installation, Operation, and Maintenance Instructions for the REGAL Approach and Landing System 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. Final Study Report for Proposed Landing Control Set AN/GSN-6, Gilfillan Bros. Inc., 1959.

4. Technical Proposal for Experimental Elevation Position Determining System for Landing, Gilfillan Bros. Inc., 16 August 1958.

2.4 Applicable Patents

The following patents were originated prior to or in the course of performance under this contract:

Case No.	Title of Invention	Inventor/s
456*	Packaging Device Printed Circuits Board	Lester D. Alexander
460	Radar Antenna System for Height Measurements	L. L. Sanders
461	Gain Controllable Radio Frequency Detector	L. L. Sanders
471*	Microwave Interferometer Linear Array	Dr. Frederick M. Weil

In addition, the Basic concept of the REGAL equipment is covered under Patent application Serial No. 15233 (Case No. 441), filed 16 March 1960, entitled AUTOMATIC LANDING CONTROL SYSTEM USING SCANNING INTERFEROMETER BEAMS, a Gilfillan Bros. Inc. proprietary patent application.

* Note: Invention concepts conceived and established prior to the receipt of contract.

2.5 Identification of Technical Personnel

Listed below are the technical personnel and the total man-hours expended by each during the period covered by this report. Included are the man-hours expended by the Field Engineering personnel at the NAFEC installation through 30 May 1960.

NAME	TOTAL MAN-HOURS
Alexander, L.	194
Bailey, J. S.	560
Blocher, H. L.	687
Bolton, C. S.	1148
Clark, S.	1033
Conlan, B.	548
Cutler, B.	287
Dutton, W.	1784
Ell, G.	1822
Friend, C.	2535
Goodwin, J.	332
Guttmann, E.	192
Kruger, B.	754
Meyer, T.	173
McGowan, J.	654
Okamura, J.	227
Romandia, R.	1828

NAME	TOTAL MAN-HOURS
Sanders, L. L.	2709
Smith, C.	2065
Stayboldt, G.	329
Stein, R.	205
Thacher, H.	1017
VanAlstyne, A. G.	165
Weil, F.	714
Wilke, W.	179
Minor Consulation & Services	1024
Total hours	24,164

3. DETAIL FACTUAL DATA

This section presents a condensation of the more important technical data obtained during the development of the Experimental Elevation Position Determining-System for Landing (REGAL equipment). This data is presented as background material to assist in the evaluation and testing of the REGAL Equipment and to aid in the establishment of future automatic landing system concepts.

There is included a technical discussion of the design and comments derived during the design of various parts of the system. Since complete testing was not performed within the scope of this contract, only the results of preliminary testing are presented. Also presented in this section is a summary of an investigation into the procurement of a rapid-scanning antenna to work the REGAL equipment. A technical write-up of the Coordinate Converter unit is given on almost a handbook level.

3.1 Results of Design Effort

In the REGAL equipment there are several areas of equipment design that were relatively unexplored. One by-product of an experimental program of this nature that may become very useful is a discussion of the design approach, the performance achieved, and the major problem areas encountered. In this section these results of the equipment design are presented.

3.1.1 Antenna Design. - The REGAL equipment employs a mechanically-scanned antenna system which uses two identical nodding antennas driven from the same shaft but in opposite directions, and energized only during alternate time intervals. This technique makes efficient use of the available scan time and yet restricts the electrical scan to the downward half of the scan cycle for each antenna. The antennas are of the linear array type consisting essentially of 16-foot lengths of waveguide feeding a row of 226 collinearly arranged dipoles inserted into one of the broad walls of the waveguide. On both sides of the row of dipoles fins run along the whole length of the array, forming a corner reflector for the r-f energy in the H-plane. The combination of dipole and fins thus produces a 3 db beamwidth of about 47 degrees in the horizontal plane (Figure 3-1).

A short run of waveguide coming from the rotating joint is connected directly into the narrow wall of the array at the exact center of its 16-foot length. The input waveguide and the scanner form a series-branching H-plane tee, dividing the transmitter power equally between the two array halves, the energy in the two halves being in phase but traveling in opposite directions. Susceptive irises in the rear wall of the array and the narrow walls of the input waveguide insure a good impedance match and an even division of power.

The orientation of the dipoles along the array is such that the energy radiated by one half of the array is 180 degrees out of phase with the energy radiated by the other half. The array, in effect, consists of two independent 8-foot long arrays with identical patterns but of opposite phase. This arrange-

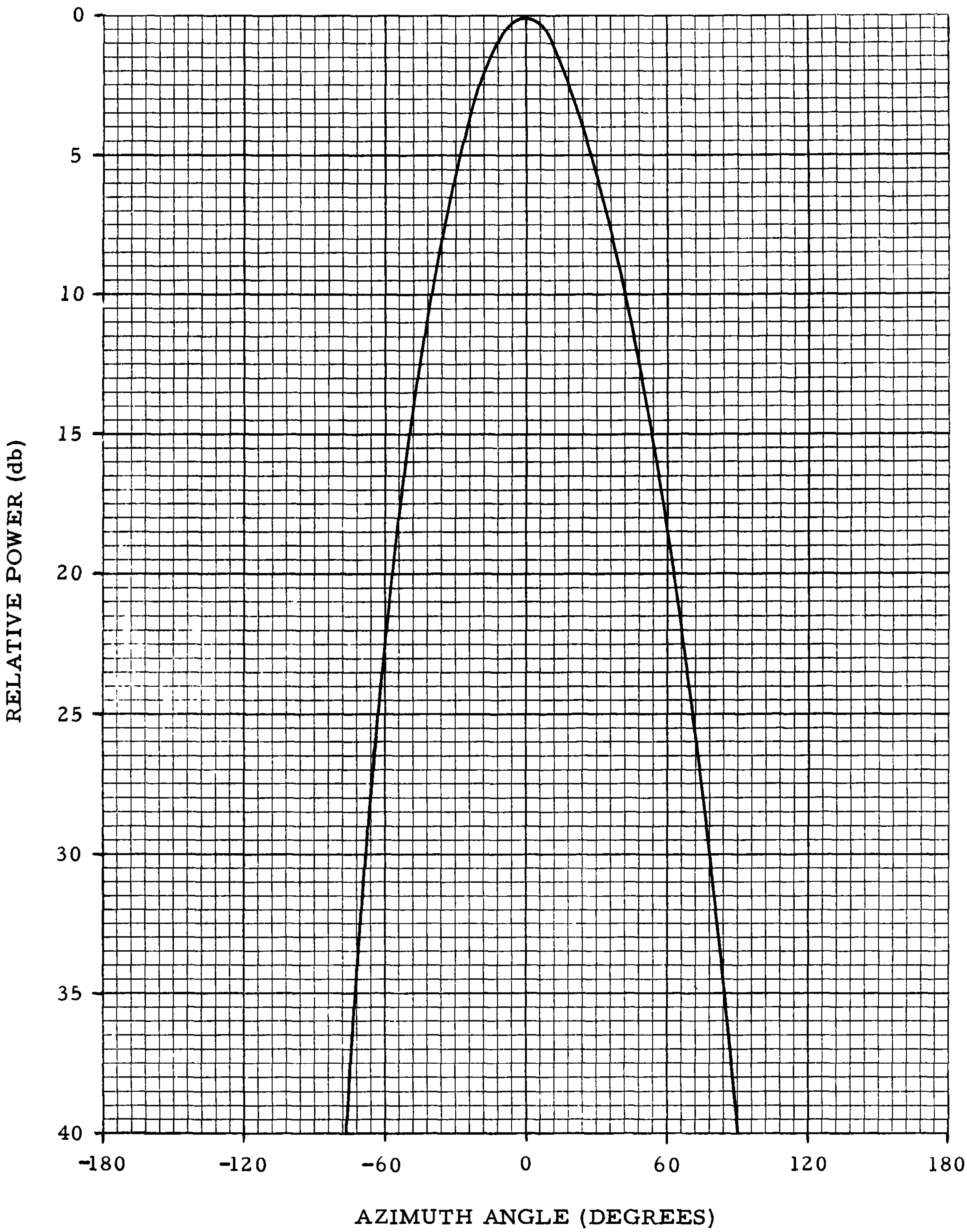

Figure 3-1 - Horizontal Pattern at 9000 Mc ment results in the desired interferometer pattern with a null in the exact center of the pattern.

The arrays are broadside traveling wave type, with a small amount of excess power dissipated in loads at their far ends. Traveling wave arrays have excellent impedance matching except at resonance and, for that reason, are usually operated at frequencies off resonance. In the non-resonant condition, however, the direction of radiation of the center of the beam is not exactly broadside but at some angle with respect to the array normal, and this angle will vary with a variation in transmitter frequency. The beam-angle shift (1-degree endfire) of the two halves has been compensated in the REGAL antenna for the design center frequency by introducing a slight bend into the waveguide at the centerfeed point. This causes the radiation from both halves to be exactly parallel at the operating frequency.

If the antenna is operated off frequency, the beam-angle shift of one half of the array will be exactly equal to the beam-angle shift of the other half, but will be in the opposite direction thereby causing the interference null to lie exactly along the array normal. At frequencies other than the normal operating frequency the overall pattern, however, will be broader, but no boresight error will be introduced into the indicated scan angle.

At frequencies very far from the design frequency, the null starts to fill in and becomes increasingly shallow, thereby limiting the usefulness of this design to a relatively narrow frequency band (approximately 1 percent of the center frequency). This limitation of band-width could be eliminated in any future design by making the bend in the center of the array adjustable and calibrating the bend angle in terms of frequency. This would make it possible to obtain a narrow interference pattern with a very deep null for any operating frequency over a relatively broad band. In view of the application of the REGAL antenna solely as a research tool, this refinement did not appear warranted.

An alternate approach to the solution of the inherent frequency sensitivity of traveling wave arrays for the REGAL application would have been to feed the array not from the center but from one end. In this case the radiation from the two halves would always be in parallel directions regardless of the frequency, and the quality of the interference pattern would remain high over a large frequency band. This, however, would cause the direction of the interference null to vary with frequency, requiring detailed and accurate calibration of this scanning action and continuous monitoring of the transmitter frequency. It was felt early in the development of the REGAL system that the limitation in bandwidth of the center-feed system was much less of an operational disadvantage than the loss in accuracy of angle data inherent in the end-feed system.

During the early design phase it had been planned to illuminate the arrays with a Dolph-Tchevycheff distribution to optimize beamwidth and sidelobe level. It was found that, for an array of the given length, this type of distribution would result in impractical values for the end dipoles. Probe lengths would become usuable only for sidelobe levels below 35 db, but this would result in excessive beamwidths. Consequently, a simple, easily obtainable gable illumination was chosen with an edge illumination of -10 db for each half of the array. Theoretically, this would result in a sidelobe level about 3 db higher than would be possible with a Dolph-Tchebycheff illumination and a pattern of equal beamwidth.

While it was expected that the level of the first side lobes of the interference pattern would be of the order of -23 db, the actual measurements show considerably higher side lobes (see Figures 3-2 and 3-5). The fact that the side lobe level and structure is unsymmetrical about the interference null and that there are some differences in side lobes between the two arrays, indicates that this problem is to a large degree one of manufacturing tolerances. This appears to be an area in which further work of both theoretical and experimental nature might prove quite fruitful.

Figures 3-2 through 3-9 show test patterns in the vertical plane for both antennas under varying conditions. Figures 3-2 and 3-3 are the patterns of one of the antennas (No. 1) at 9010 mc and 9015 mc, respectively, while Figures 3-4 and 3-5 show the comparable patterns for the other antenna (No. 2). These four patterns are practically alike over the main portion of the beam, indicating that the two antennas are identical and that no appreciable pattern change takes place over this narrow frequency band. The patterns are clean and narrow with the null consistently much more than 30 db below the peak of the pattern.

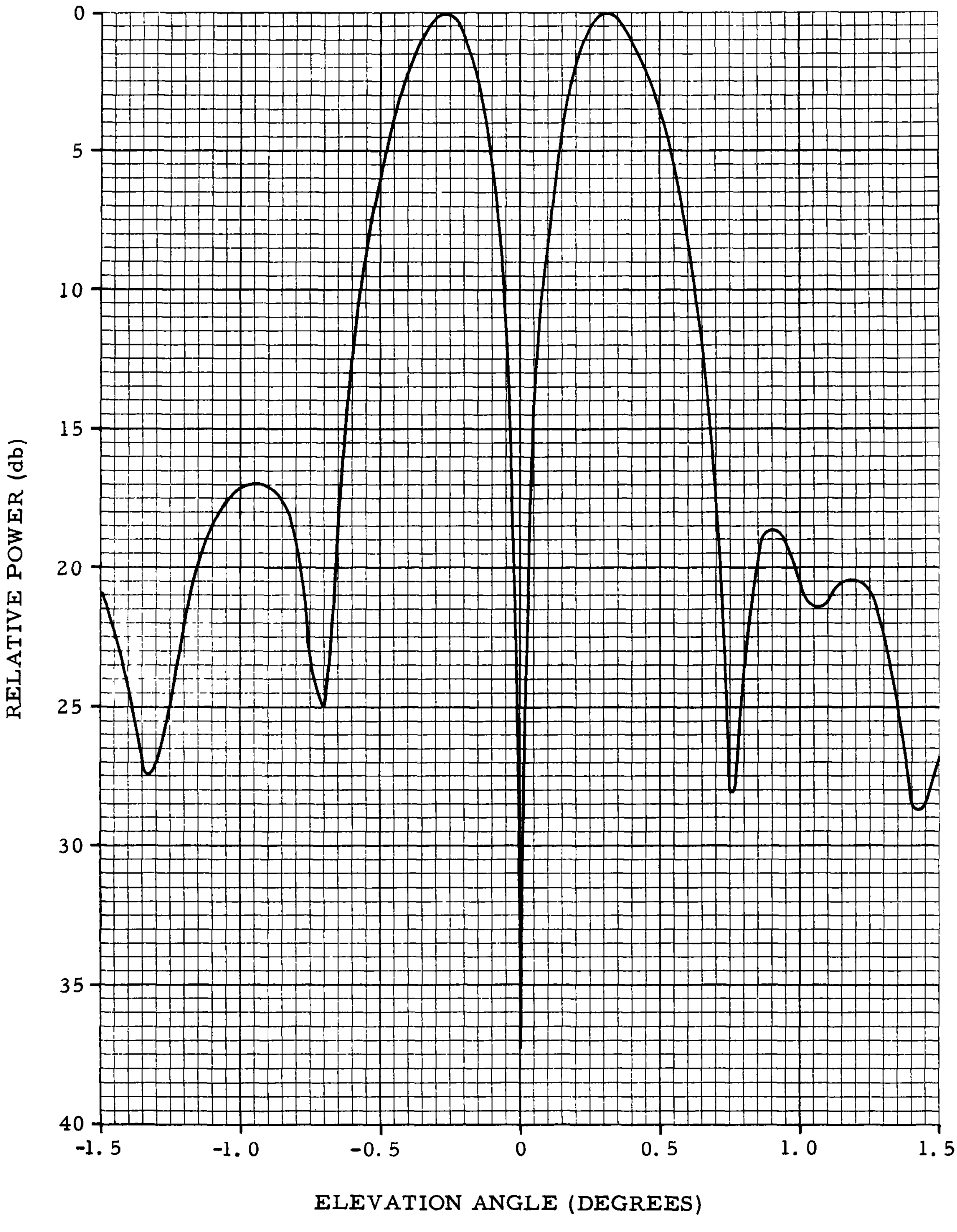

Figure 3-2 - Vertical Pattern, Array No. 1 at 9010 Mc

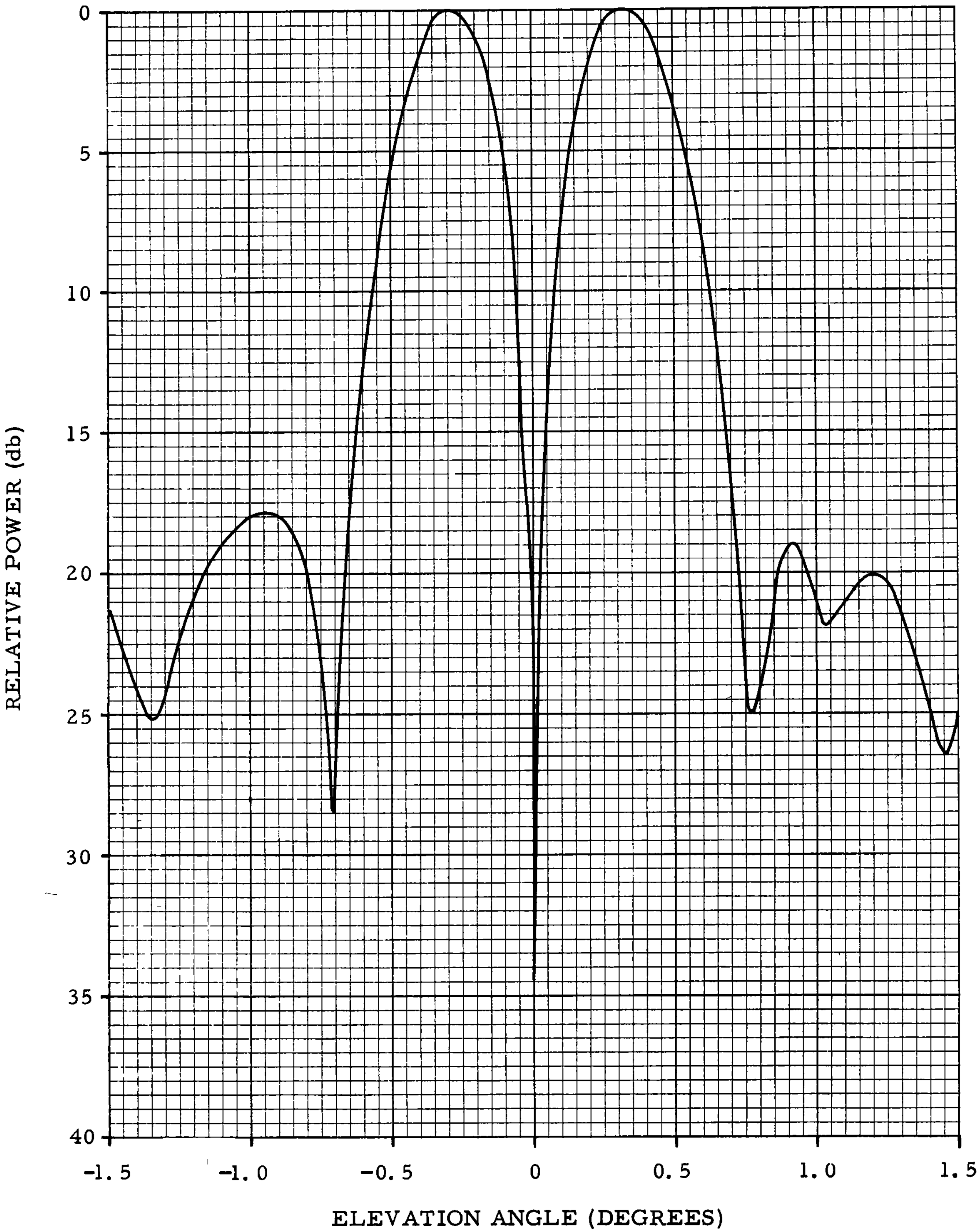

Figure 3-3- Vertical Pattern, Array No. 1 at 9015 Mc

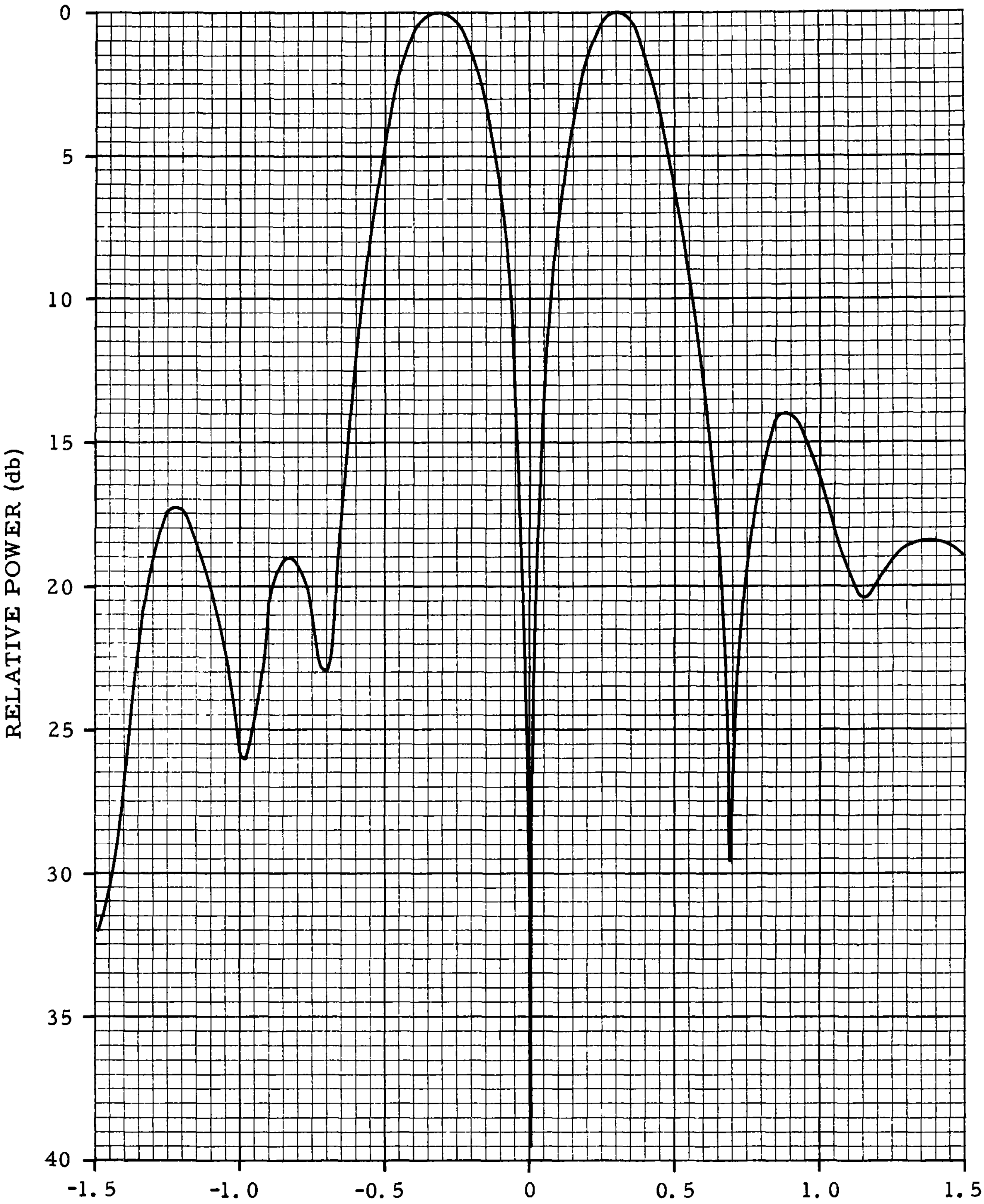

Figure 3-4 Vertical Pattern, Array No. 2 at 9010 Mc

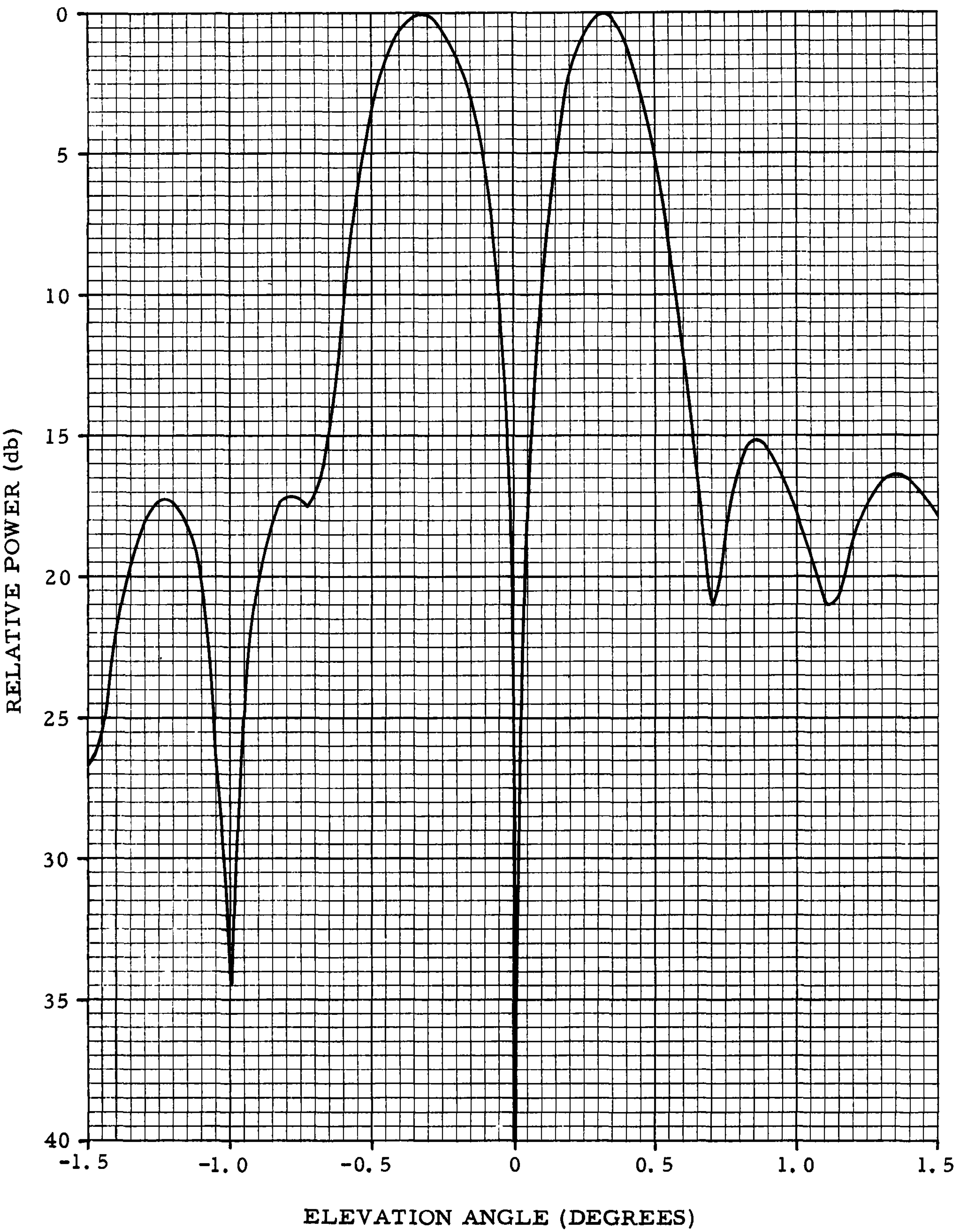

Figure 3-5 - Vertical Pattern, Array No. 2 at 9015 Mc

The arrays were originally designed for operation near 9080 mc, and the bend in the center of the arrays was calculated for that frequency. On testing, however, it was found that the narrowest patterns were obtained in the neighborhood of 9010 mc to 9015 mc, indicating that the direction of radiation from each individual array half was not exactly at the predicted angle. This appears to be due to mutual coupling between the dipole probes, which introduces a phase shift into the array waveguide. Since, for the purposes of the REGAL system, operation in the neighborhood of 9015 mc is as acceptable as operation near 9080 mc, no redesign is contemplated.

Figures 3-6 and 3-7 show the interference pattern at 9040 mc and 9080 mc, respectively, with the gradual widening of the main portion of the pattern quite apparent. It is significant, however, that the null remains excellent at 9040 mc, and is still more than 30 db below the pattern maximum at 9080 mc.

Two additional patterns are reproduced in Figures 3-8 and 3-9. These are vertical plane patterns, as before, but taken 10 degrees and 20 degrees, respectively, off the main axis in the horizontal plane. While the main pattern remains narrow, the null starts to fill in and is only about 23 db below the pattern maximum at the 20-degree cut. Actual operation of the system will have to show how far the airplane can be off the beam axis in the azimuth plane until the null becomes too shallow for accurate determination of its elevation angle.

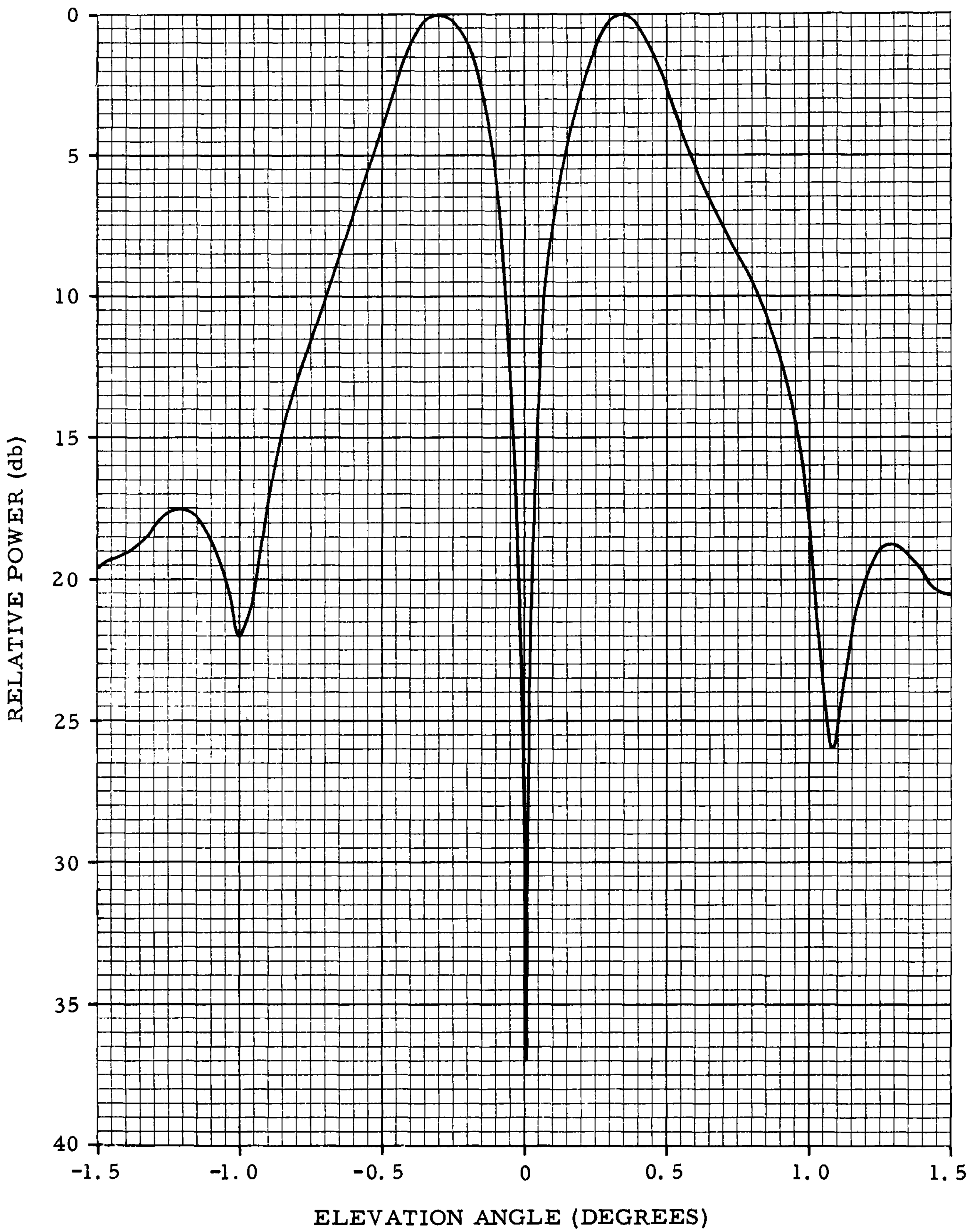

Figure 3-6 - Vertical Pattern, Array No. 1 at 9040 Mc

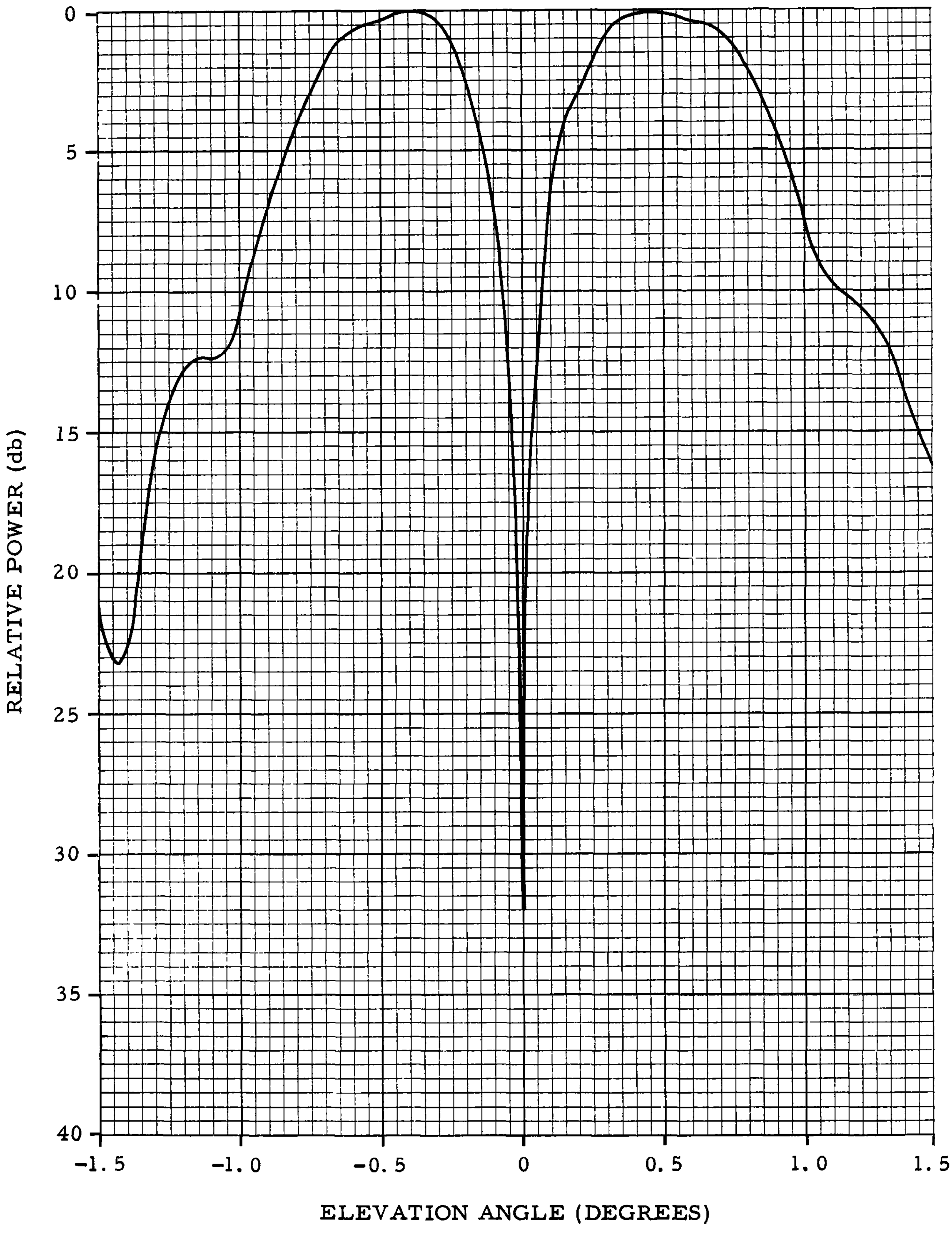

Figure 3-7 - Vertical Pattern, Array No. 1 at 9080 Mc

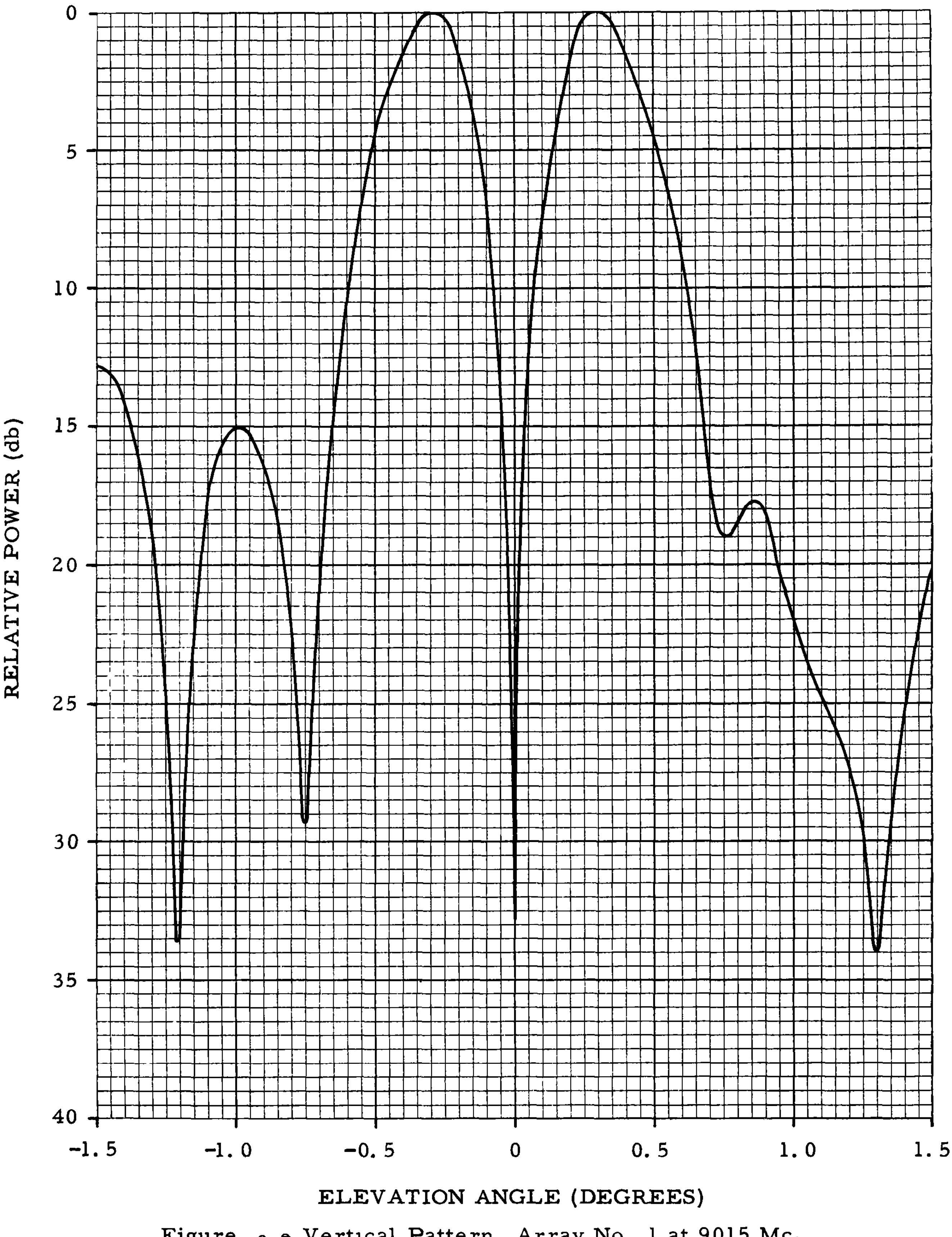

Figure 3-8 Vertical Pattern, Array No. 1 at 9015 Mc, -10° Offset in Horizontal Plane

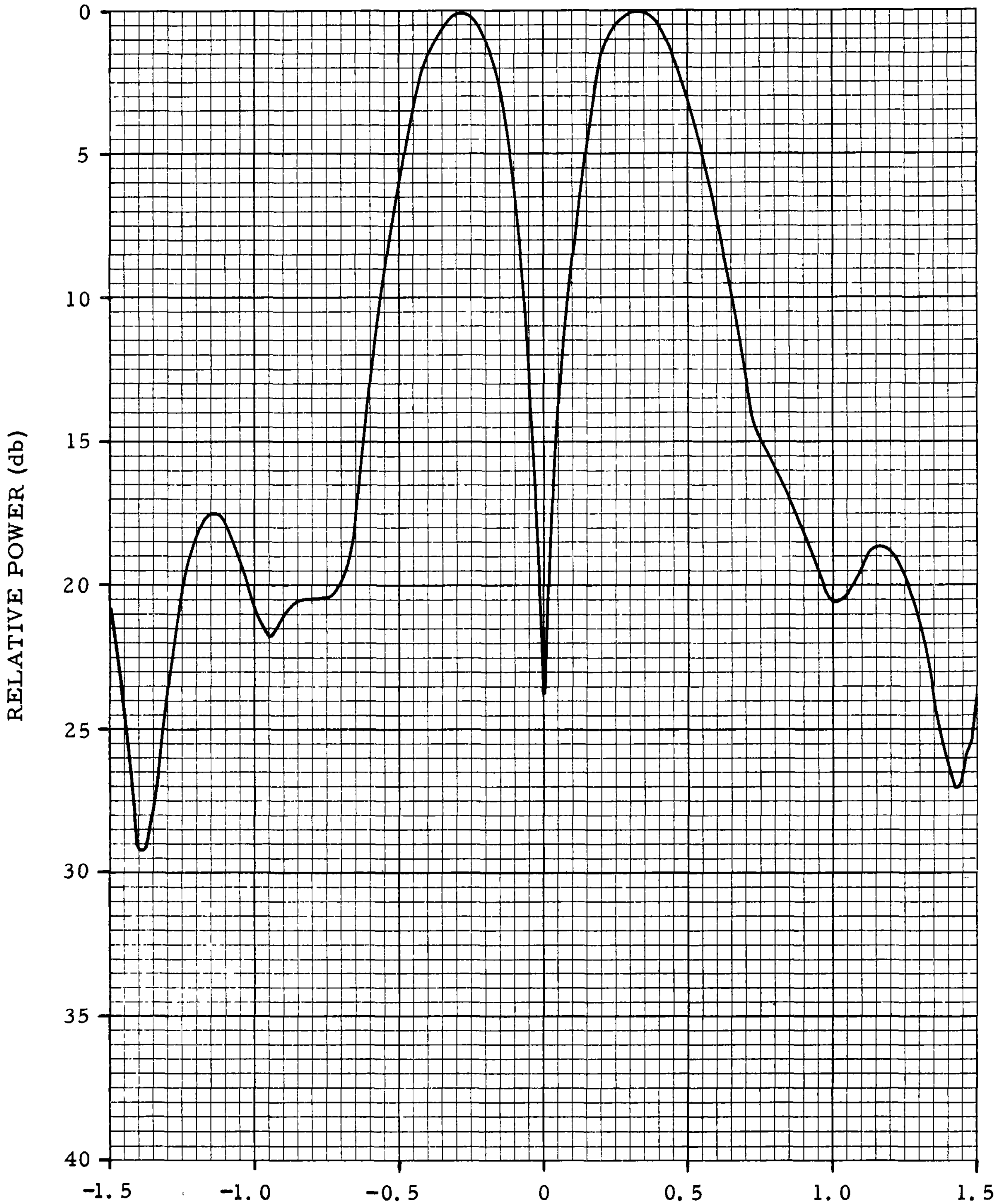

Figure 3-9- Vertical Pattern, Array No. 1 at 9015 Mc, -20° Offset in Horizontal Plane

3.1.2 Antenna Support Structure. - The antenna chosen for the REGAL system is composed of two mechanically-scanned linear arrays. The beamwidth requirements of the system require the linear-array antennas to be 16 feet in length; and the data-rate requirements of the system require each antenna to scan at a rate of 2 1/2 cycles per second.

One of the major considerations in the design of the antenna system has been to fabricate a support structure (boom) for the linear-array antennas with adequate stiffness to insure that there will be no distortion of the antenna boom position during the scan cycles. The system requirements demand that the support structure deflection correspond to less than 0.02 degrees of beam position error, with a design goal set at 0.01 degrees.

The following paragraphs present a discussion of the boom stiffness problem and the design approach that was followed. The results of simulated dynamic boom deflection tests are also presented. In addition, there is a brief discussion of other approaches to performing a more rigorous test of the boom deflection under dynamic conditions.

Boom stiffness is divided into two aspects: (1) deflection under dynamic load, and (2) mechanical resonances and vibrations.

3.1.2.1 Deflection Under Dynamic Load. - Although the requirements called for a boom designed for a scan rate of 2 1/2 cycles per second, it was decided to try to provide a capability of a scan rate of 4 cycles per second with a crank speed of 240 rpm. On this basis, the design for the boom was established. It would consist of two identical 8-foot halves joined together to form the 16-foot boom.

The center of the boom would be 6 inches by 10 inches and the ends 2 inches by 2 inches. Each half would be made in three sections. The section nearest the center would be 1/4-inch aluminum, the intermediate section 3/16-inch aluminum, and the end section 1/8-inch aluminum.

Although the two halves of the boom are the same in structure, they react differently under a dynamic load (during scanning), because the lower half is attached to a driving mechanism. At the start of the downscan, the top half of the boom bends backwards. Inertia of the lower half tends to bend it forward; however, the pull from the connecting rod (which must overcome inertia forces of both halves) overcomes the inertia of the lower half sufficiently to bend it backwards. Thus both halves bend backwards, and the null at the center of the pattern is undisturbed. Even in a pessimistic case where the lower half of the boom does not bend, the overall angular null displacement would correspond to only one-half the angular deflection of the top half of the boom.

After fabrication of the antenna, tests were made for a simulated dynamic load. These tests and their results are described in paragraph 3.1.2.3 and shown in Figures 3-10 and 3-11.

3.1.2.2 Mechanical Resonances and Vibrations. - A test was made to determine the resonant frequency of the boom. It was found to be 80 cycles per second in the plane of motion and 62 cycles per second at right angles to the plane of motion.

The antenna boom was assembled to the pedestal and drive mechanism. At a speed of 5 scans per second (2 1/2 cps per antenna), the operation was very smooth. No significant vibrations were detected. At a speed of 10 scans per second (5 cps per antenna), there was excessive vibration in the support and drive structure. This was caused by an unbalance of the crank. Weight had been added to the crank for a static load, but weight had not been added to offset the mass of the antenna boom being moved. After this correction and several other minor corrections, the operation was very smooth. It is the general opinion that the mechanism will have long life at 5 scans per second, limited life at 10 scans per second.

At the time of delivery, the equipment had 520 hours of operation at a speed of 5 scans per second. The only changes made during this time were the bearings on the connecting rods. The bearings at the boom end were changed after 200 hours from rod end bearing to Universal joint bearings to eliminate the freedom of the rod in twist. The bearings at the crank end were replaced before delivery.

3.1.2.3 Test Description. - Tests were made to evaluate the deflection of the antenna array and its boom support structure under dynamic loading conditions. For reasons of economy this test was made under static conditions by measuring the deflection due to simulated dynamic loads.

For the simulated dynamic load test, the boom was clamped in a horizontal position, leaving a cantilever of 96 inches.

Weights were attached at six positions on the cantilever section (see Figure 3-10). These weights corresponded to reversal loading, imposed on the boom by the mass of the section and the distance from the center of rotation, based on a 5-scan rate of 2.5 cps and a 10-scan rate of 5 cps.

The weights used are listed in Table 3-1.

TABLE 3-1

WEIGHT CALCULATIONS

Distance From Center	WT 2.5 cps	WT 5 cps
8 in.	15.62 lb.	62. lb.
24 in.	41.30 lb.	165. lb.
40 in.	47.09 lb.	188. lb.
56 in.	56.25 lb.	244. lb.
72 in.	45.43 lb.	221. lb.
88 in.	45.45 lb.	221. lb.

Double dial indicators with a resolution from -0.0005 to +0.0005 were mounted to take readings at positions I_1 to I_5 (Figure 3-10 and Table 3-2). Indicators I_1 through I_3 were located at underside of boom for minus readings. Indicators I_4 and I_5 were located at clamped section for pluse readings.

TABLE 3-2

TABULATION OF TEST DATA

5-SCAN RATE (2.5 cps) TEST NO. 1				
I_1	I_2	I_3	I_4	I_5
0.0695	0.0195	0.0155	0.	0.
10-SCAN RATE (5 cps) TEST NO. 2				
0.181	0.028	0.026	0.0025	0.

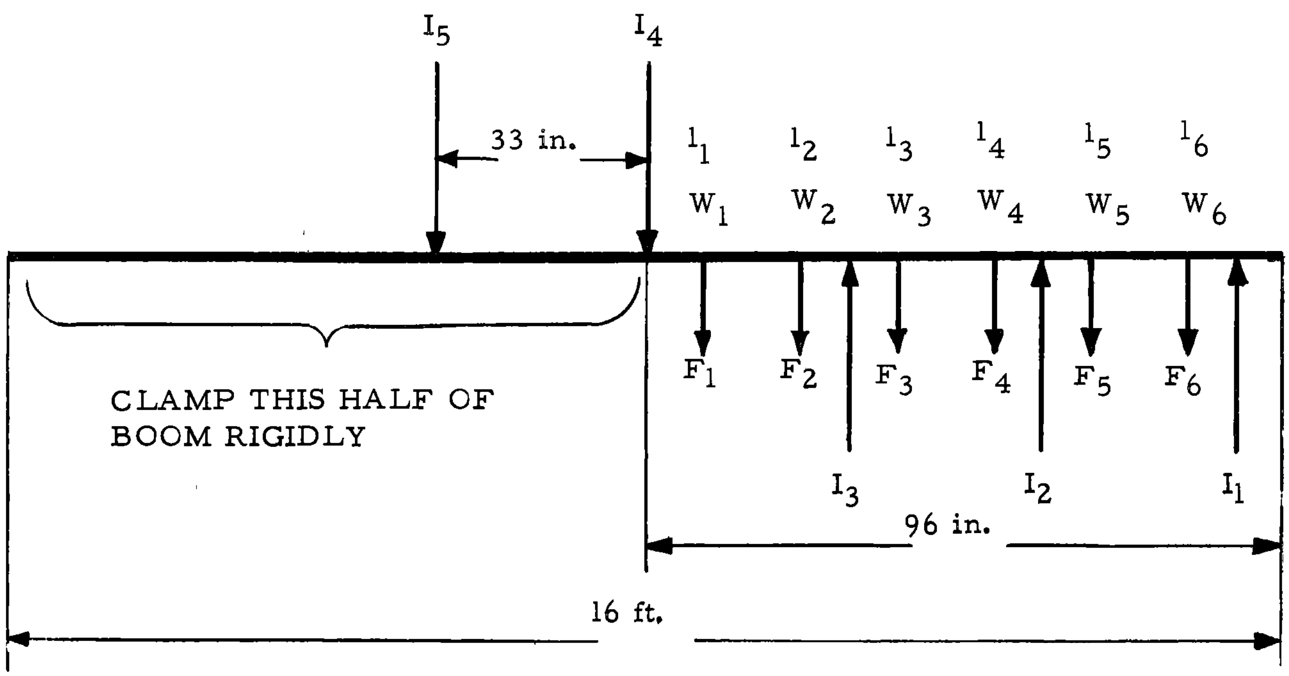

Figure 3-10. Diagram of Simulated Load on Antenna Boom

DEFLECTION CURVE ANTENNA BOOM SIMULATED
DYNAMIC LOADING
5-SCAN RATE 2.5 CPS - 10-SCAN RATE 5 CPS

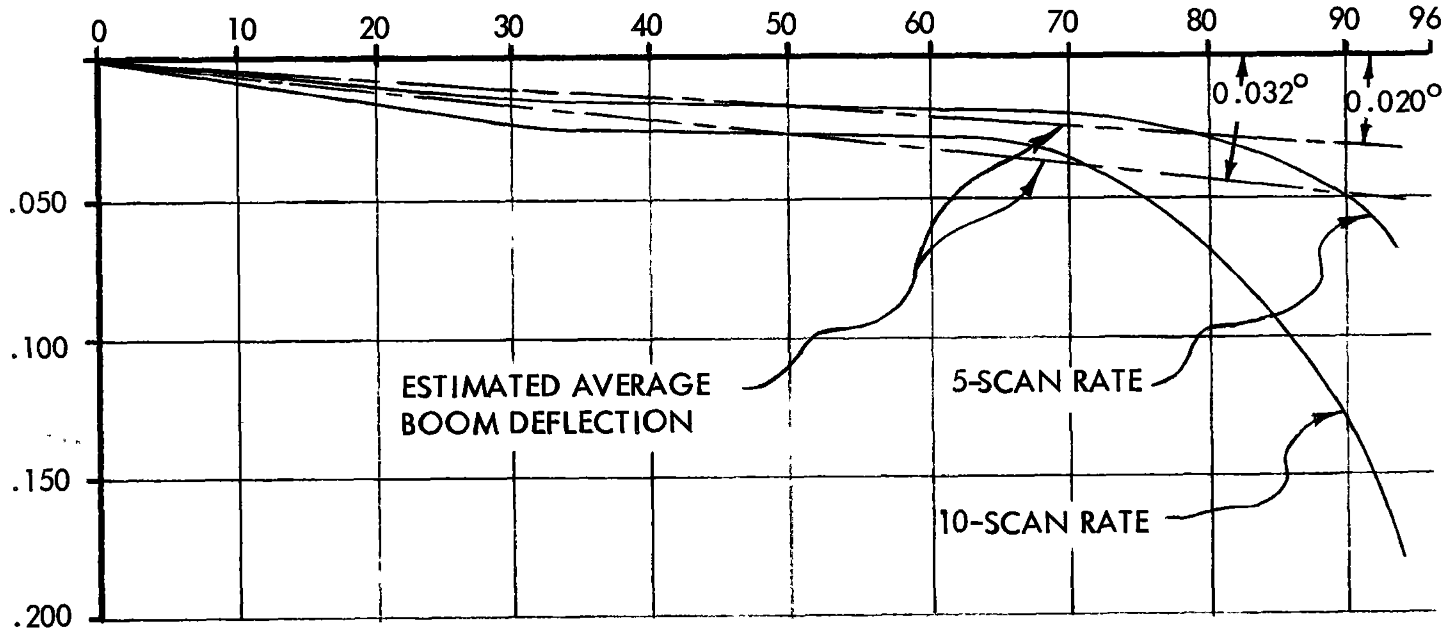

Figure 3-11.

The average boom deflection was estimated from the data plotted in Figure 3-11 by drawing a straight line through the midpoint (deflection at 50 in.). This arbitrary estimate results in an average deflection for half of the boom of 0.020 degrees and 0.032 degrees for scan rates of 5 and 10 per second respectively. The resultant error in the position of the null in the antenna pattern (assuming no deflection in the other half of the boom) would be 0.01 degrees for 5 scans per second and 0.016 degrees for 10 scans per second. However, the overall accuracy of this test is probably not better than ± 50 per cent.

This simulated boom deflection test does confirm that the boom design is adequate for a 5 scan-per-second rate and that it would not detract from system performance very much at 10 scans per second.

3.1.2.4 Other Test Methods. - Consideration was given to other possible methods of making a dynamic test of the antenna boom deflection. Two of these methods are discussed briefly for future reference.

Dynamic tests of the boom could be made using a number of strain gauges attached to the boom. But since strain gauges will only measure the surface elongation over a relatively small length, it would be difficult to derive the angular deflection of the boom. One direct technique to obtain the angular deflection would be to set up the boom for static deflection tests using dial indicators, and then, to adjust the loading weights until the strain gauge readings recorded under dynamic conditions could be reproduced. It is felt that this type of strain gauge test would be accurate to approximately 20 per cent or 30 per cent but was not undertaken because of the time and equipment required.

A second dynamic test of the boom stiffness was considered which involved taking high speed photographs of the antenna position during operation. In order to detect deflections in the order of 0.05 inches to 0.1 inches the photographs would have to be approximately "life size" and have a sharply focused reference grid as a background. The camera would have to be located less than 2 feet from the tip of the boom and have good depth of focus. Since the tip of the boom moves approximately 0.015 inches in 50 microseconds, the shutter speed would have to be less than 1/20000 of a second. In order to produce a photo under dynamic conditions that could be compared with a similar photo taken under static conditions, the camera would have to be accurately synchronized to one mark of the data take-off system.

Although it is felt this photographic deflection test could yield data accurate to approximately 10 per cent, it is not considered practical within any reasonable time and budget limitations.

3.1.3 Data Take-Off System. - The data take-off system originally designed for the REGAL equipment consisted of a tone wheel geared to the shaft of the antenna and fixed magnetic pickup heads. This technique proved difficult of achievement and was abandoned early in the system test phase in favor of an optical data take-off technique. This section presents a brief description of the advantages and disadvantages of the two techniques.

3.1.3.1 Magnetic Data Take-off

3.1.3.1.1 Description. - The magnetic data take-off originally designed was composed of a 10-inch diameter steel wheel and pinion shaft mounted on the antenna pedestal. The pinion was driven at a 10:1 speed ratio by a gear segment attached to the antenna boom. Two sets of notches were engraved across the rims of the wheel. The spacing of the notches on one edge of the wheel was 16 times greater than the other, making a designation of coarse and fine wheels. Proximity type magnetic pickups, requiring head spacing of approximately 0.0004 inches from the outer rim of each disc, were mounted on brackets.

3.1.3.1.2 Magnetic Data Take-off Problems. - Several problems were found after testing the first set of tone wheels due to design and fabrication methods. Problems ascribed to the tone-wheel design are, in general, due to the high inertia of the tone wheel.

a. The tone-wheel inertia resulted in excessively high torque loading on the gears, especially at the ends of the scan. The loading caused gear wear and unacceptable backlash conditions.

b. The tone-wheel inertia caused the tone-wheel shaft to bend between the pinion and the first ballbearing. This resulted in changes in the spacing between the pickup head and the tone wheel.

c. The choice of a large steel wheel with small notches cut in it to form a tone wheel offered very poor resolution to the magnetic pickup heads.

Problems ascribed to the tone-wheel fabrication are as follows:

a. The tone wheels were found to have a rim run-out of 0.004 inches. Resurfacing reduced this to 0.002 inches but did not eliminate it.

b. The correct tone-wheel bearing preloading was not achieved at first, which resulted in excessive bearing play and wear.

c. Tone-wheel shaft alignment for parallelism betwen it and the scan-axis shaft was not readily attainable. This contributed to the gear wear and backlash problems.

3.1.3.1.3 Second Model Tone-Wheel. - Redesign of the tone wheel reduced the total wheel inertia from 0.1834 slug-in^2 to 0.1101 slug-in^2. As the new wheel was fabricated in one piece, better tolerances were maintained. Although it was not used to any great extent, a substantial improvement was noted in operation.

3.1.3.1.4 Conclusion. - In conclusion, it was decided that basically the magnetic data take-off was an acceptable approach. However, in evaluating both the magnetic data take-off and the optical data take-off (paragraph 3.1.3.2) methods, the optical data take-off provided greater advantages.

3.1.3.2 Optical Data Take-off. - The optical data take-off is comprised of an engraved scale mounted on a sector, which is attached directly to the antenna support boom and an optical system that derives electrical signals in accordance with the scale markings. The optical system contains an illuminator, a lens system similar to a microscope objective, and two semiconductor photo devices. The photo devices and their respective preamplifiers generate pulses when the image of a reflective line on the scale passes an aperture. There are coarse and fine engravings on the scale and two corresponding channels of the photo-devices and amplifiers as in the magnetic data take-off.

The optical data take-off system has one important, basic advantage. An optical image can be focused and magnified over a relatively long distance, which allows a great reduction in mechanical tolerances.

The optical data take-off operated very satisfactorily with few disadvantages. The areas where improvement may be sought in future designs are:

a. The photo device was chosen for response speed and availability, but it has a very low sensitivity. A more sensitive unit should be obtained for future designs.

b. It is felt that the technique of a reflective scale and front illumination could be improved upon. The use of a transparent scale and back illumination appears definitely more attractive.

3.1.4 Transmitter-Modulator. - The REGAL transmitter-modulator accepts the coded-data trigger pulses generated by the encoder unit and provides the necessary drive to the magnetron oscillator, which transmits the coded rf signals. A detailed description of these units is given in the Handbook of Instructions for the REGAL Transmitting Set. The design of these units resulted in generally satisfactory performance, but several problems were encountered during the system testing that indicated reliability and component life was less than that desired. There are several areas where a slightly different design approach should be taken if the transmitter-modulator equipment were to be re-designed.

3.1.4.1 High Duty Cycle. - Many of the problems that were encountered during the field tests were due to the high duty cycle. The worst problem was caused by the high repetition rate and the high instantaneous duty during the scan followed by a long dead time. This on-off operation tended to cause poor regulation by the regulated power supplies which were not adequately designed for use under these transient conditions.

3.1.4.2 Modulator Drivers. - Because of space limitations it was necessary to double-pulse the first driver for the first and seventh pulse of each coarse data group. Considerable design effort was expended to achieve the capability to re-pulse the driver in 6.5 microseconds for the seventh pulse. There is still some variation in amplitude between the first and seventh pulses. If the required space had been available, the use of seven drivers would have been very desirable.

3.1.4.3 <u>4PR60A Switch Tubes.</u> - The use of four 4PR60A tubes in parallel was a weak point in the equipment design concept. The use of these tubes in parallel leads to problems with parasitic oscillations. It is also very difficult to attain equal loading of the tubes when they are used in parallel. The high duty cycle and the on-off operation in the REGAL system greatly aggravated these problems. Since the original equipment was designed, modulator tubes with a much larger capacity than the 4PR60A have become available. The use of one of these tubes to replace the four 4PR60As' in a next generation equipment would do much to make the modulator more reliable.

3.1.4.4 <u>Magnetron Operation.</u> - The high duty cycle of the REGAL system posed another problem since no magnetron specifically rated for operation at this duty cycle was available. Since the Raytheon RK-6249A has proven itself to be a very rugged and reliable tube it was chosen for the REGAL transmitter. By keeping the peak-pulse current down to about 15 amperes, it was possible to operate at the high duty cycle and still keep the average input power at a reasonable level. The de-gaussed tubes that were recently installed (May, 1960) should give much better performance at the reduced pulse current. Raytheon would very likely be able to supply these de-gaussed tubes as a stock item if the quantity involved were large.

3.1.4.5 <u>Delay Cable.</u> - The long and bulky delay cable used at present is not very desirable. It is very possible that a lumped constant delay line could be designed that would approximate the delay cable and would be a small fraction of the volume and weight of the present cable. Another approach would be to design a modulator circuit that would damp out the reflected pulses and prevent interaction. The system would eliminate the need for a delay cable.

3.1.4.6 Field Test Performance.

a. Diode Failures:

High voltage silicon diodes are used in the high voltage power supply. These silicon diodes are a fairly new product, and while they have very good potentialities, some problems remain to be solved before their potential reliability will be realized. The diodes now installed in the high voltage power supply have a current and peak inverse voltage rating 50 per cent greater than the original diodes. Surge limiting resistors have also been installed.

b. 4PR60A Failures:

When the system was first tested, the life of the 4PR60A modulator tubes was very short. The high duty cycle and on-off operation is very hard on the 4PR60A tubes. A considerable improvement in tube life was obtained by redesign of the driver units. By increasing the grid drive to the keyers, the conductance during the pulse was increased and the plate dissipation decreased. The 4PR60A keyer tubes are still the weakest point in the transmitter modulator.

3.1.5 Airborne Receiver. - The REGAL airborne receiver is of the crystal video type containing an rf preselector cavity, a video detector crystal, and a high-gain video amplifier with provisions for agc. The performance of the receiver based on preliminary measurements appears to be satisfactory and has closely approached all the desired specifications, as follows:

a. The receiver sensitivity is approximately -48 dbm for decoding (decoding threshold set approximately 7 db above rms noise), which is within 3 db of the theoretical expectation.

b. The agc control range is adequate to operate at ranges down to approximately 500 feet from the transmitter.

c. The dynamic range for decoding, with a fixed agc voltage, is approximately 25 db referenced to rf input signals.

d. The system coding and the rf preselection make the system immune to signals on adjacent rf frequencies.

In the original proposal for the REGAL system and in the subsequent study effort, consideration was given to the comparative advantages of a crystal-video receiver and a superheterodyne receiver. It was decided to design a crystal-video receiver for the REGAL airborne unit, in order to demonstrate the simplicity and small size achievable with this type of approach. It was admitted that the performance might be slightly inferior, but the crystal-video receiver would be less expensive in production.

The primary advantages of a superheterodyne receiver would be as follows:

a. A superheterodyne receiver will offer a sensitivity improvement over a crystal-video receiver of approximately 40 db. Although preliminary tests indicate a crystal-video receiver will provide adequate system coverage over a range of more than 10 miles, there is very little safety factor in the overall system for additional refinements such as: reduced transmitter power, increased wide-angle azimuth coverage, flexible airborne installations using coaxial cable, or omni-directional airborne antenna installations.

b. A superheterodyne receiver will offer improved dynamic range capabilities over a crystal-video type. The automatic gain control capabilities of the superheterodyne receiver are much better, and the dynamic range capabilities for any one value of agc voltage are definitely superior.

It is therefore concluded that, although the REGAL receiver performance has proved to be satisfactory, consideration should be given to an overall system configuration which allows for at least an optional superheterodyne type receiver.

3.1.6 Range Tracker. - The range tracker, utilizing synchronous replies from the ground transmitter, is capable of acquiring and tracking any target within the 10-mile range of the airborne receiver at velocities in excess of 600 knots. The overall range accuracy appears to be $\pm$100 feet or one per cent, whichever is greater.

The range tracker consists primarily of the following four circuits: (1) the time modulator, which, with reference to a start trigger, generates the fundamental time reference of the tracker; (2) the coincidence detector and stretcher circuits, which, during tracking, produce an output voltage proportional to the relative positions between the target reply and the early and late gate crossover point; (3) the integrator, which integrates the error voltage produced by the stretcher circuits to produce an output voltage proportional to range; and (4) the acquisition detector circuits, which control the operating mode of the range tracker.

3.1.6.1 Acquisition Techniques. - Acquisition in the REGAL range tracker is accomplished via a wide-narrow gate detection system and a tracking relay.

When the reference trigger is received, a flip-flop in the time modulator is set. This flip-flop switches on the bootstrap integrator and provides wide gates, through the de-energized tracking relay, to the coincidence detector and stretcher circuits.

The time modulator produces two sets of tracking gates continuously regardless of the state of the tracking relay. When the tracking relay is not energized, a pair of wide gates produced by the time modulator flip-flop are applied to the coincidence detector circuitry.

If a synchronous range reply is present, it will fall in one or the other of the wide gates provided by the flip-flop. Thus, an error voltage will be produced at the output of the coincidence detector. The polarity of this voltage will be of such a polarity as to cause the integrator to slew the narrow early-late gates toward the range reply.

As soon as the synchronous range reply coincides with either of the narrow tracking gates for an interval exceeding approximately 2 seconds, the acquisition detector will energize the tracking relay. Energizing of the tracking relay applies the narrow (Early-late gain overall width $\cong$ 3 usec. Tracking notch width $\cong$ 1 usec.) gates to the coincidence detector and stretcher circuits. Thus the tracking loop is closed and will remain closed until touchdown or loss of signal.

From the above explanation, it will be noted that the acquisition and tracking loops are the same. The differences between the two modes of operation lie entirely in the width of the early-late gates utilized during each phase. This characteristic leads to certain disadvantages which are discussed in paragraph 3.1.6.4.

3.1.6.2 Velocity Memory. - The REGAL range tracker employs a quasi-velocity-memory technique that provides a good measure of tracking enhancement for short-duration losses of signal but avoids the complex stability problems associated with the true double-integral velocity-memory technique. Velocity memory is approximated by summing a direct channel with a long time constant lag channel, which has a substantially higher gain. The direct channel preserves the loop stability for the sampled data rate of 5 scans per second. The lag channel significantly increases the velocity error coefficient without adversely affecting transient response of the loop. If the signal is lost momentarily, the lag channel will preserve aircraft velocity information for a number of seconds.

The acquisition detector will drop the range tracker into acquisition mode if range reply is lost for a time in excess of 2 seconds. During this interval the velocity memory information will decay approximately 10 per cent.

3.1.6.3 Time Modulator Tests. - The time modulator in the range tracker utilizes a bootstrap integrator to generate the reference ramp. The accuracy of the entire range tracking system depends largely on the linearity of the bootstrap circuit.

System analysis in the early stages of the REGAL program indicated that the ramp linearity had to be greater than 0.5 per cent for ranges between 0.5 n mi and 4 n mi. Thus the greatest portion of the design and testing effort was directed to producing the required ramp linearity for the short ranges.

Linearity tests performed on the time modulator, as it now exists in the REGAL equipment, were performed over the temperature range of 25 to 50°C. A maximum error of 0.926 per cent occurred at 50°C for a range of approximately 10.8 n mi. (130 usec). Ramp linearity remained consistently within 0.5 per cent of the computed straight line values for the 0.5 n mi. to 5 n mi. range interval.

3.1.6.4 Alternate Acquisition Techniques. - Since the present range tracking system is experimental in nature, several possible refinements were judged to be unnecessary to prove the basic concept and performance capabilities. Consequently there are several shortcomings in the present acquisition technique, as follows:

a. When a single loop is utilized for both modes of operation, the gain and damping constant cannot be optimized for both acquisition and tracking. An additional relay should have been added to the present range tracker in order to change the tracking loop constants during acquisition.

b. The overall width of the combined wide gates utilized for acquisition is approximately 200 microseconds. This figure represents the pulse repetition period of the range interrogation pulses, which corresponds to a range of approximately 16 miles. These gates are excessively wide. In a further improvement of the present range tracker, the acquisition gates could be reduced by a factor of 2 or more, thereby reducing the susceptibility to random interfering pulses.

In the present REGAL range tracker the loop characteristics have been so designed as to provide an acceptable compromise between the conflicting requirements of acquisition and tracking. Acquisition of a target at maximum range can be accomplished in about 33 seconds including overshoots and transition to track operation. The present tracking noise represents a range error of less than 50 feet rms.

The probability of the system being jammed during acquisition has been markedly reduced by gating the video channel "on" only during the 3.6 ms interval, during each scan that range interrogation pulses are being transmitted. Tests thus far have shown that, except for extremely adverse conditions, acquisition in the presence of interfering PRF's is acceptable.

However, for second generation trackers there are several other approaches to the acquisition-tracking problem which should be considered.

A few of the more promising approaches are discussed below:

a. Fixed Gates. - For an approach system, it may be that automatic acquisition of the ground station, as the aircraft approaches the runway, is a nice but expendable refinement. If so, the cost of the present tracker could be reduced and the accuracy of the tracking increased by adjusting the loop characteristics to satisfy narrow gate tracking requirements. Acquisition would then occur, at a preset distance from touchdown, as the aircraft passed through fixed acquisition gates.

b. Narrow, Swept, Acquisition Gates. - At the expense of increased hardware and additional design effort, the reliability of acquistion and smoothness of tracking, under adverse radar conditions, could be markedly improved by narrower acquistion gates, which are automatically swept through the 10 n mi. range capability of the trackers.

c. Double Loop, Swept, Acquisition Gate System. - At the expense of a considerable increase in hardware and additional design effort, the performance of the present range tracker can be up-graded on all counts. That is, a range tracker, whose acquisition gates are relatively narrow (15 usec for example) and swept with an acquisition loop and a tracking loop, each specifically tailored for its particular function, would represent a near optimum design.

3.1.6.5 Comments and Conclusions. - It is well to bear in mind that the present REGAL range tracker is an experimental design. Thus there are several areas where an additional design effort could be fruitfully expended with a resultant improvement in tracker performance.

a. Ground Range Decode-Reply Circuitry. - Although the range-reply portion of the ground equipment is not a part of the airborne tracker, its response characteristics affect the performance of the range tracker. That is, any jitter introduced by the ground station independent of the interrogate pulse-pair will appear as tracking noise in the range tracker outputs. It would be beneficial to future REGAL systems if the speed of the present range-decode circuitry were increased.

b. Tracking Gates. - System stability, magnitude of tracking noise and accuracy of tracking is critically dependent on the stability of the narrow early-late gates. Future trackers would benefit from additional shaping circuitry in this area.

c. Coincidence Detectors and Stretchers. - The present REGAL range trackers utilize a dual-channel scheme for early-late position detection of the target. Thus, ideally, the early and late coincidence detectors and stretchers should be identical. Practically, this is impossible to achieve and leads to range tracking with an offset. Thus far this offset introduced by lack of perfect symmetry in the two channels has not been objectionable. In addition to lack of physical symmetry, unbalanced operation can occur due to offsets, which accrue in the stretchers during the operation. The present stretcher circuits are vulnerable to this type of drift. Since these offsets occur inside the tracking loop, their effect on tracking accuracy is nullified. However, for a sample-data tracker such as the REGAL system, such offsets initiate integrator drift during the inter-sample interval and thereby contribute to tracking noise. Hence, for future systems other approaches to the target detection and stretching problem, amenable to transistors, might profitably be investigated.

d. Acquisition Time. - If the present system were modified to incorporate a tracking loop and an acquisition loop, non-linear techniques could be employed in the acquisition loop to allow rapid acquisition with minimum initial over-shoot of the target. Under these conditions acquisition time could readily be reduced to 15 seconds at maximum range.

3.2 Results of Preliminary Field Tests

The REGAL equipment is experimental in nature, designed to be used in the comprehensive test program being conducted by the FAA. For this reason, and because of the very specialized instrumentation necessary to fully evaluate this equipment, only preliminary performance tests were made. The testing conducted on the REGAL equipment was only that necessary to insure proper operation and to demonstrate conformance with the system requirements.

3.2.1 Objectives. - The objectives of the preliminary field test program were to evaluate the system performance within the confines of the Gilfillan test airport at Fontana, California, by using only readily available instrumentation. The tests were to evaluate the system accuracy on a static basis within the immediate touchdown area. Flight tests were also made to demonstrate the system coverage and general performance quality.

3.2.2 Test Installation. - The REGAL ground equipment was installed between two 2200-foot runways at the Gilfillan Airport in Fontana, California. The equipment was located approximately 1800 feet from the threshold of runway 9R and approximately 100 feet from the edge of the runway.

The modulator group of the REGAL ground equipment was housed in a wooden shelter (Figure 3-12) with the antenna, antenna drive mechanism and the data-takeoff units adjacent to the shelter (Figure 3-13).

The REGAL ground equipment test installation provided the capability to check the system both statically and dynamically throughout a relatively large touchdown region.

In order to perform static accuracy tests, a truck was set up as a portable test bed for the REGAL airborne receiver with provisions for varying the receiving antenna height from 4 to 35 feet. The truck used for housing the REGAL airborne receiver was a 2-1/2-ton stake truck with a canvas cover for shelter (Figure 3-14). Input power for the airborne receiver was supplied from a portable gasoline generator (not shown in Figure 3-14) mounted on a wooden platform, which was attached to the side of the truck.

An antenna mast was constructed and mounted on the rear of the truck. An X-band horn antenna was mounted on a sliding bracket (Figure 3-15), which was manually raised or lowered on the antenna mast centerpiece to adjust the antenna height. A coaxial lead-in cable was connected from the receiving antenna to the REGAL airborne receiver inside the truck. The airborne receiver and the test equipment were placed on a bench inside the truck.

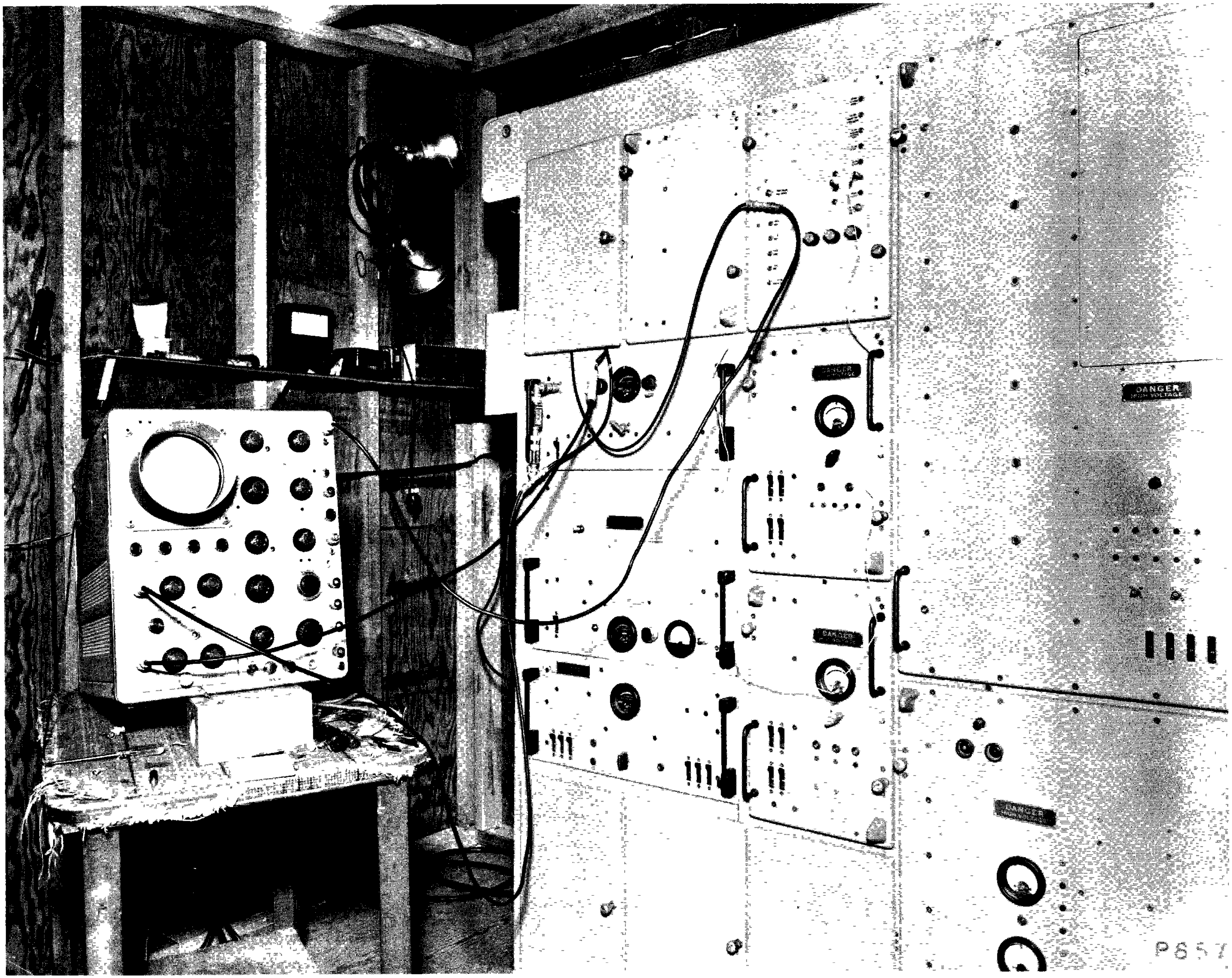

Figure 3-12. REGAL Transmitting Set Shelter, Interior View

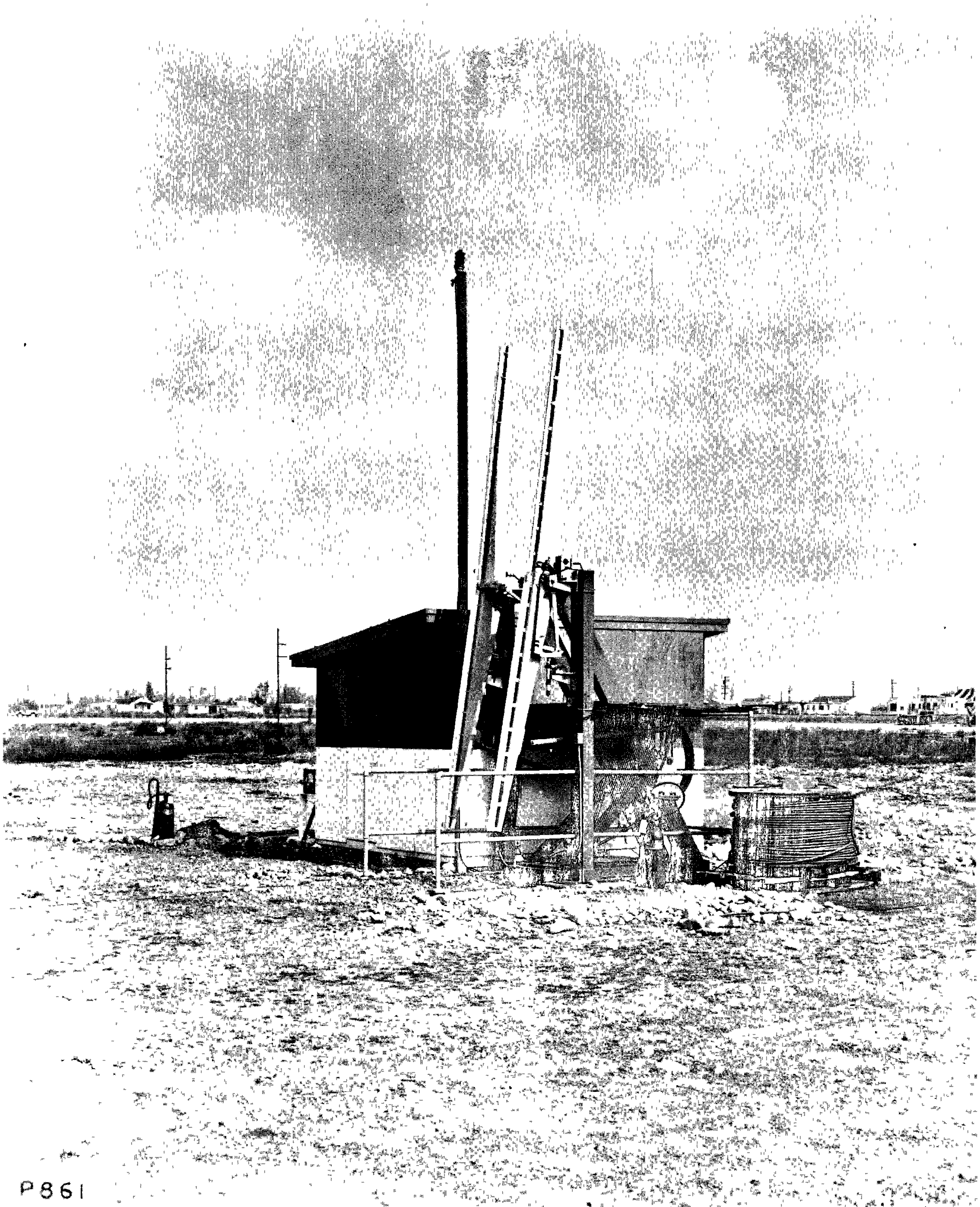

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Figure 3-13. REGAL Transmitting Set Shelter, Exterior View

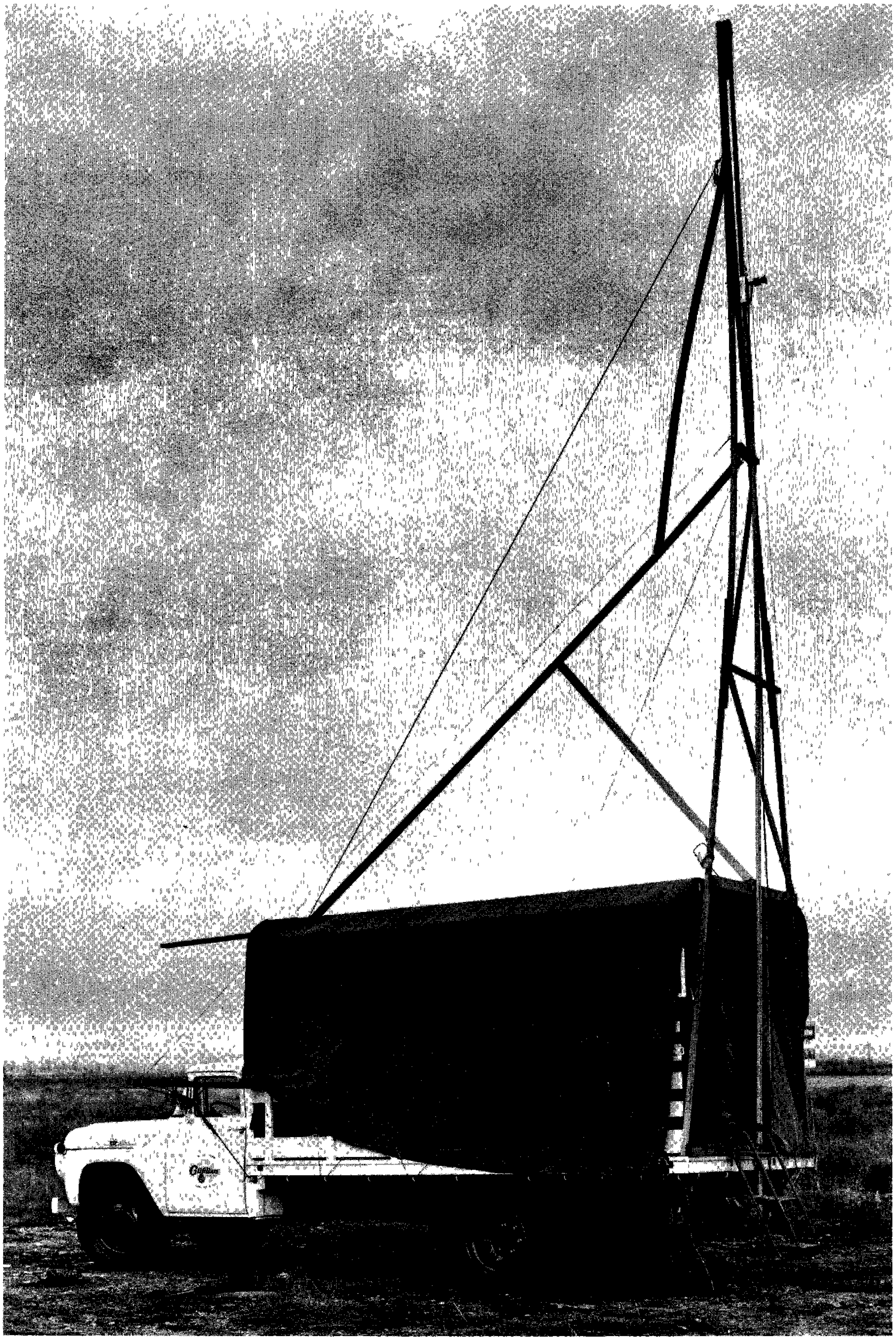


Figure 3-14. REGAL Static Testing Testing Truck With Antenna Mast

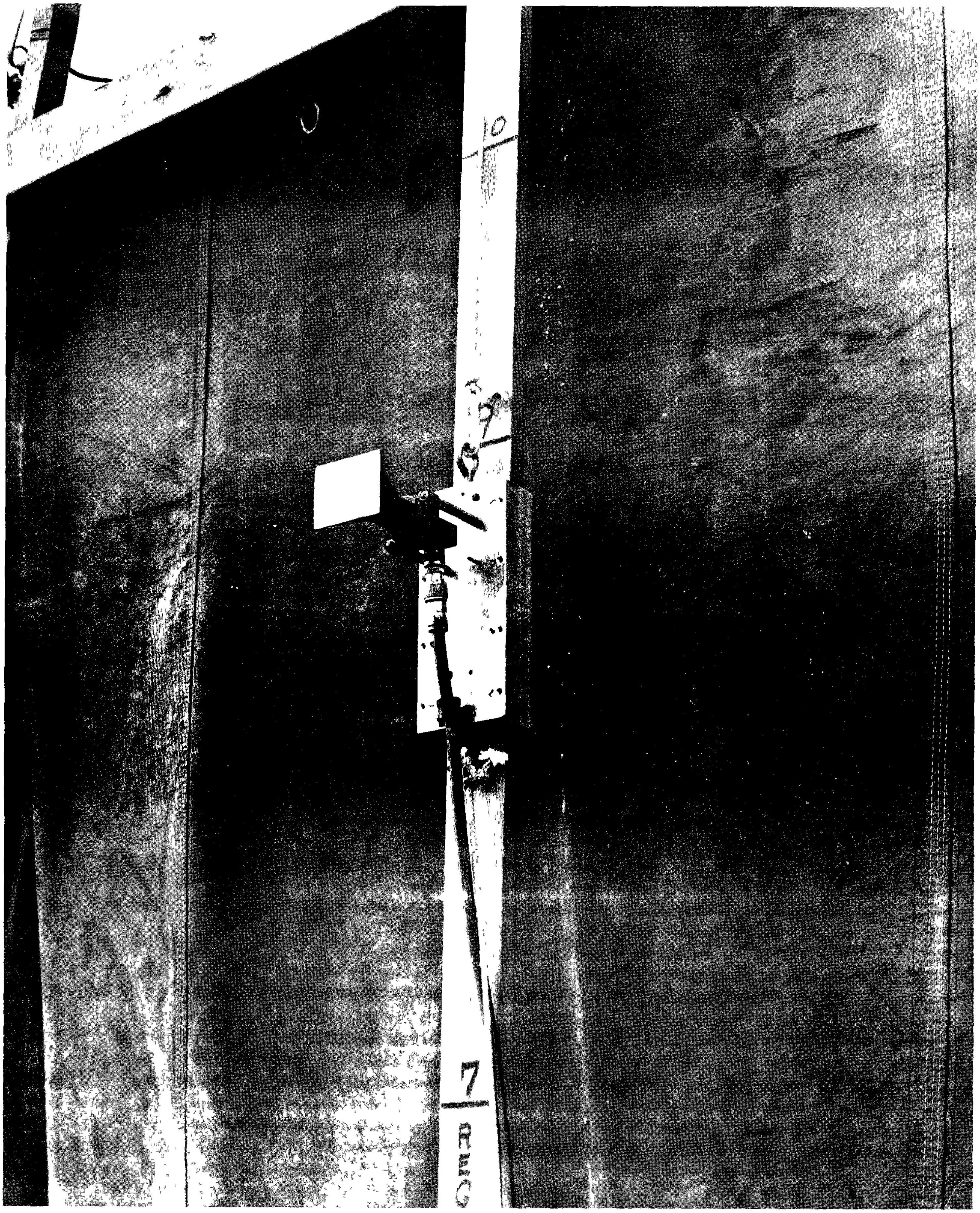


Figure 3-15. Antenna Used in Static Testing Truck

For the flight tests, a second REGAL airborne receiver was installed in a D-18S (Twin Beech) aircraft (Figure 3-16). The aircraft was provided with two antennas, one in the nose (Figures 3-17 and 3-18) and one in the aft section (Figure 3-19). The REGAL receiver outputs were connected to operate the glidepath needle and flag of an ID-249 cross-pointer indicator and a range meter (Figure 3-20). A simple altitude computing device was added to provide the pilot with a display of height information derived from the REGAL data. This aircraft installation provided the capability to test the dynamic performance and the coverage of the REGAL system throughout the entire approach region.

A Sanborn dual-channel chart recorder was also installed in the aircraft to provide a permanent qualitative record of the range and elevation angle voltages observed during the dynamic performance of the REGAL system.

3.2.3 Angle Accuracy Tests. - Angle data accuracy tests were made at five sites in the touchdown region: 1700-foot range, 1200-foot range, and 800-foot range on the centerline of the antennas and 1200-foot range with 400-foot offset, both left and right of the antennas. The truck was set up over previously surveyed marker stakes. The antenna height was varied in one-foot increments from 4 to 35 feet. Before each run the exact calibration of antenna height was checked

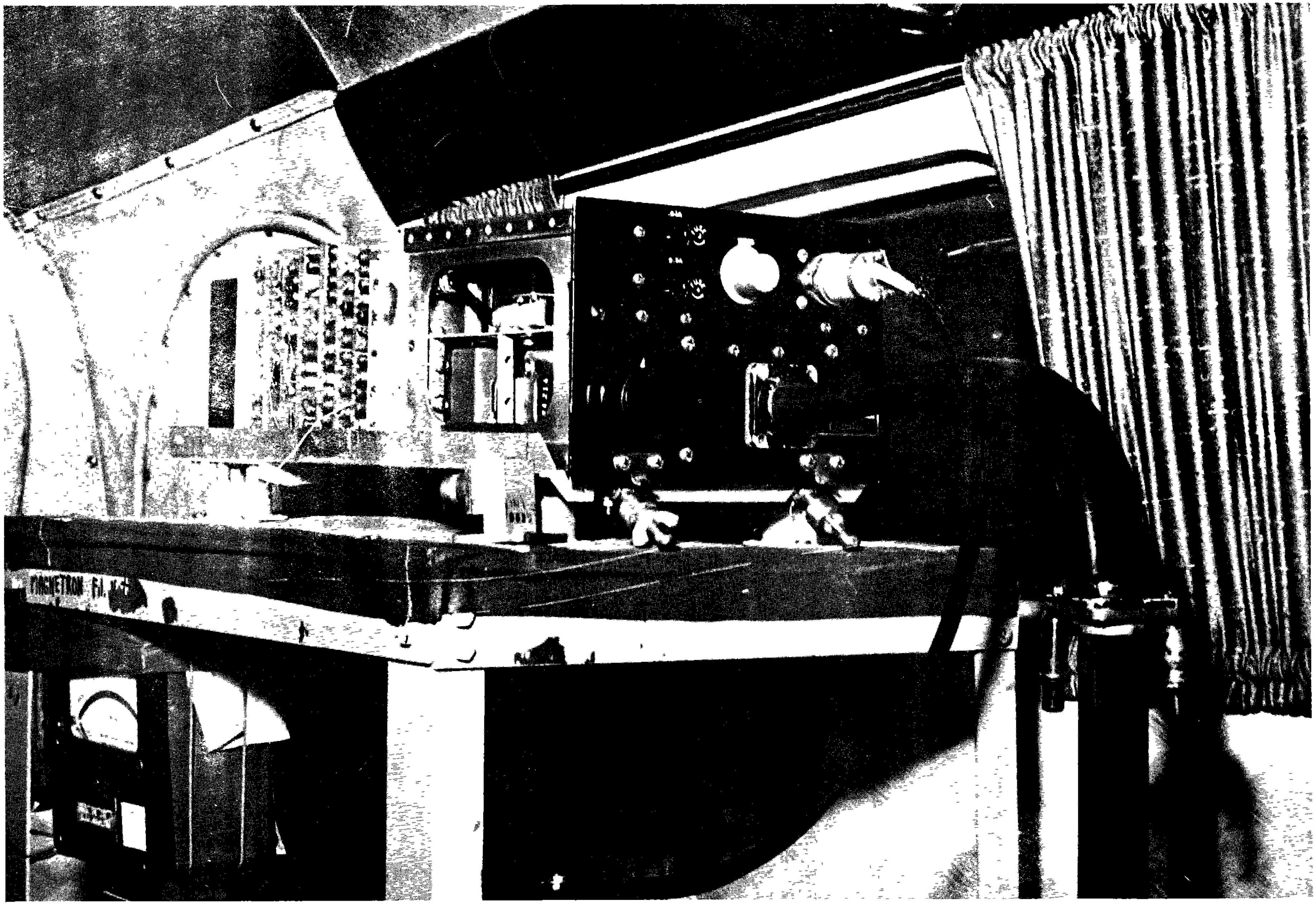


Figure 3-16. REGAL Receiver-Converter Installation in D-18S Aircraft

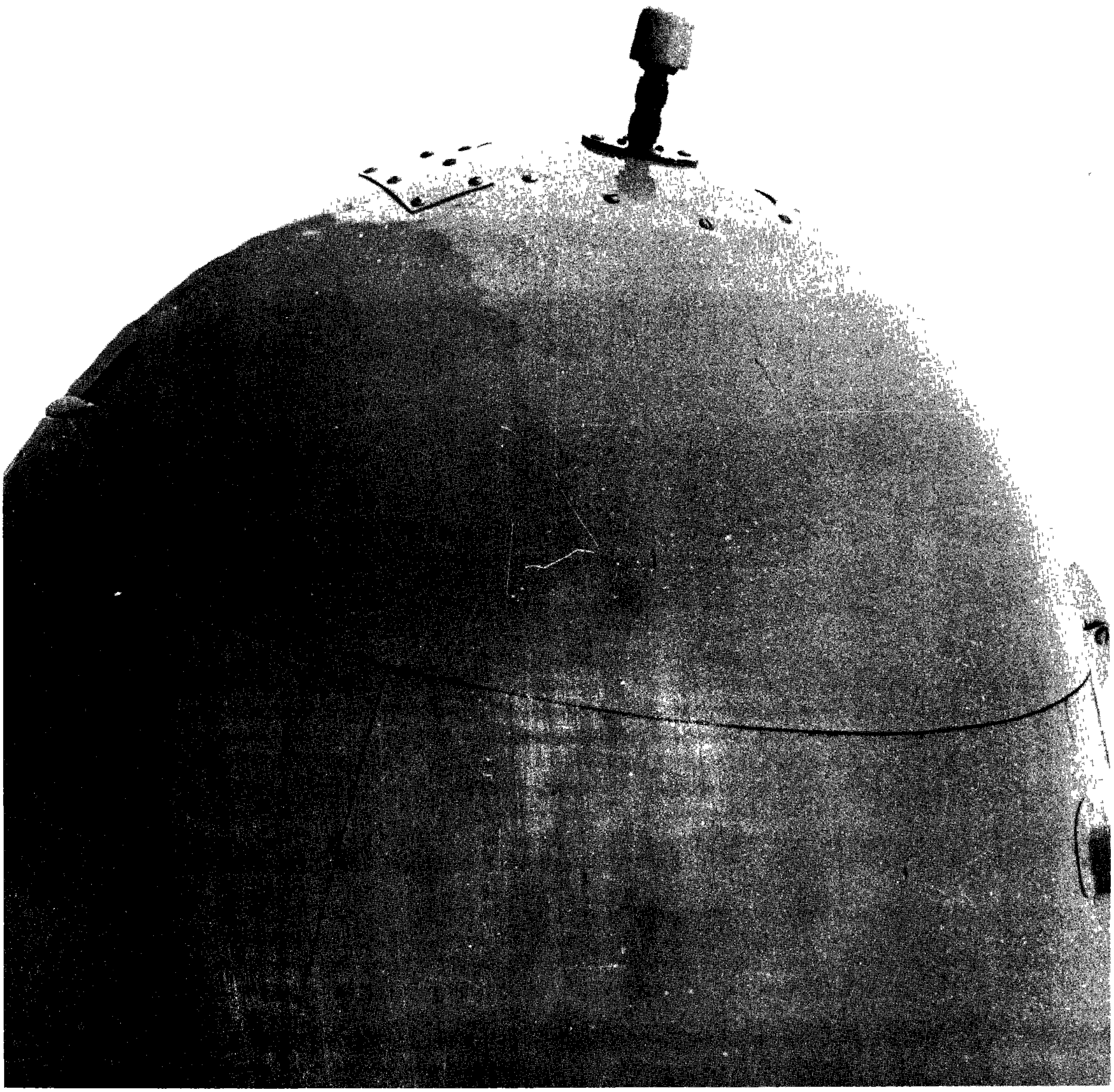


Figure 3-17. Nose Antenna Installation on D-18S Aircraft

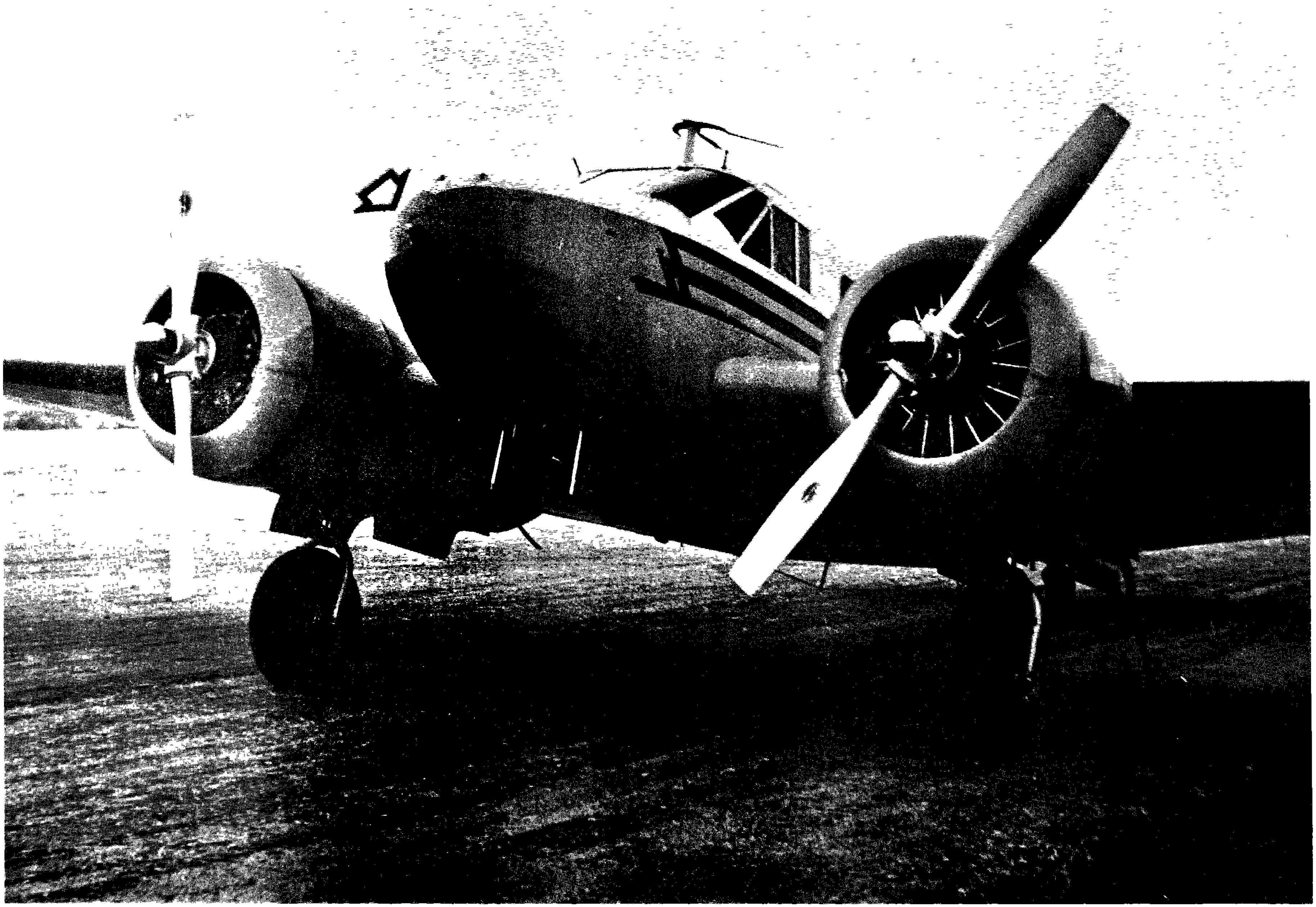


Figure 3-18. Location of Nose Antenna on D-18S Aircraft

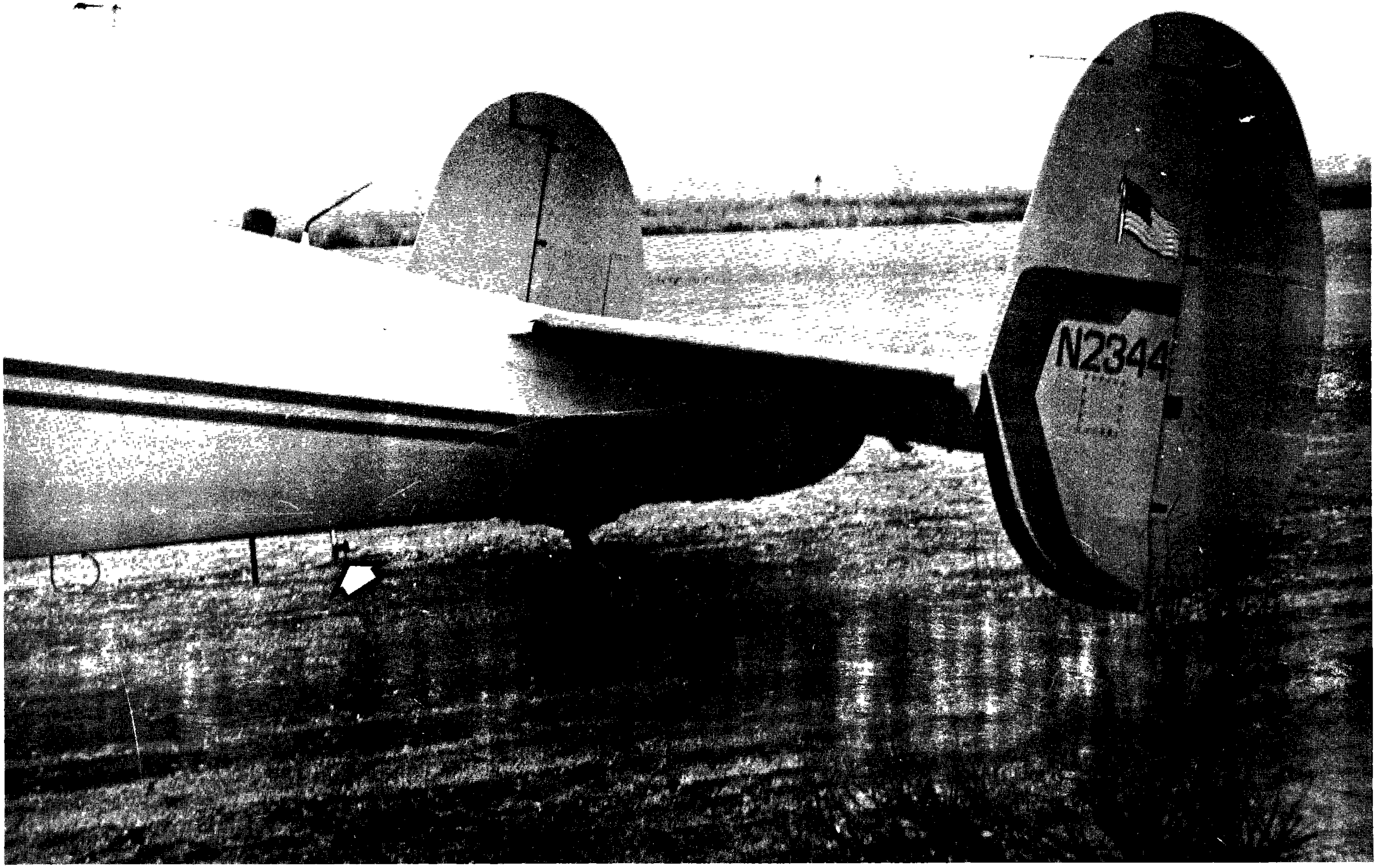


Figure 3-19. Location of Aft Antenna on D-18S Aircraft

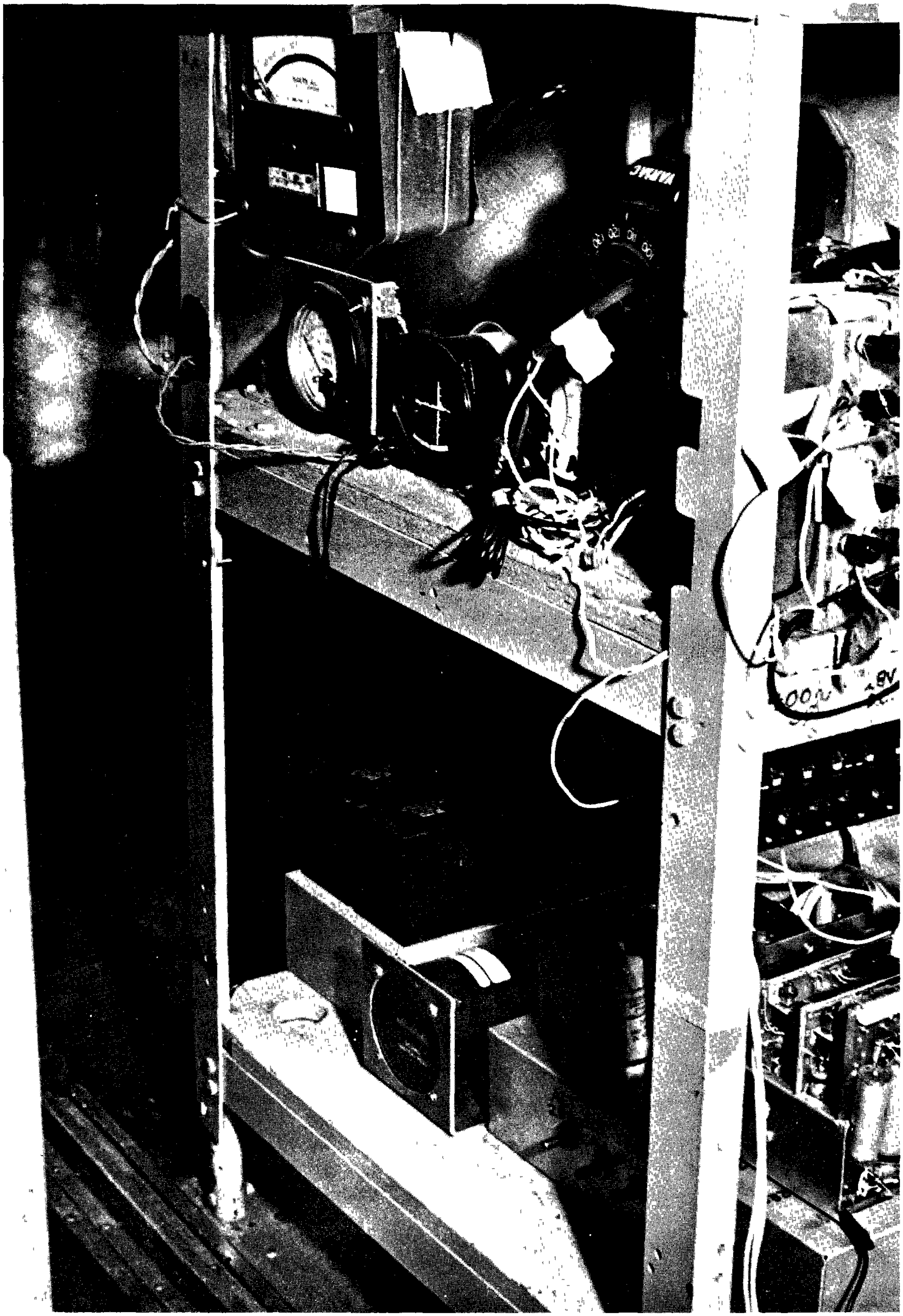


Figure 3-20. ID-249 and Range Meter Installation In D-18S Aircraft

by means of a surveyor's transit which was set up at the transmitter site. Elevation angle data was recorded at each antenna position. The results of the static angular accuracy tests are plotted in Figure 3-21 vs the theoretically calculated value. Figure 3-22 shows a typical data sheet from which these curves were plotted. In Figure 3-21 the recorded elevation angle data is indicated with an X for the left antenna and with an 0 for the right antenna. The theoretically calculated value is shown by the straight centerline with a tolerance of 0.05 degrees indicated by the boundary lines.

Separate curves for the two (left and right) ground antennas were plotted because it was discovered during the test program that the installation alignment was slightly inaccurate. In mounting the antenna support yokes, one scan axis was not made truly horizontal. The data take-off units were adjusted so that the beams coincided along the system centerline. When tests were made off the system centerline, it was found that there was a constant difference between the data from the two antennas. This problem has been corrected in the installation at NAFEC.

3.2.4 Range Accuracy Tests. - Range accuracy tests were made at ranges of 800 feet, 1200 feet, and 1800 feet. The range accuracy was determined by measuring the d-c analog voltage on a precision voltmeter. (The range voltage was also recorded on one channel of the

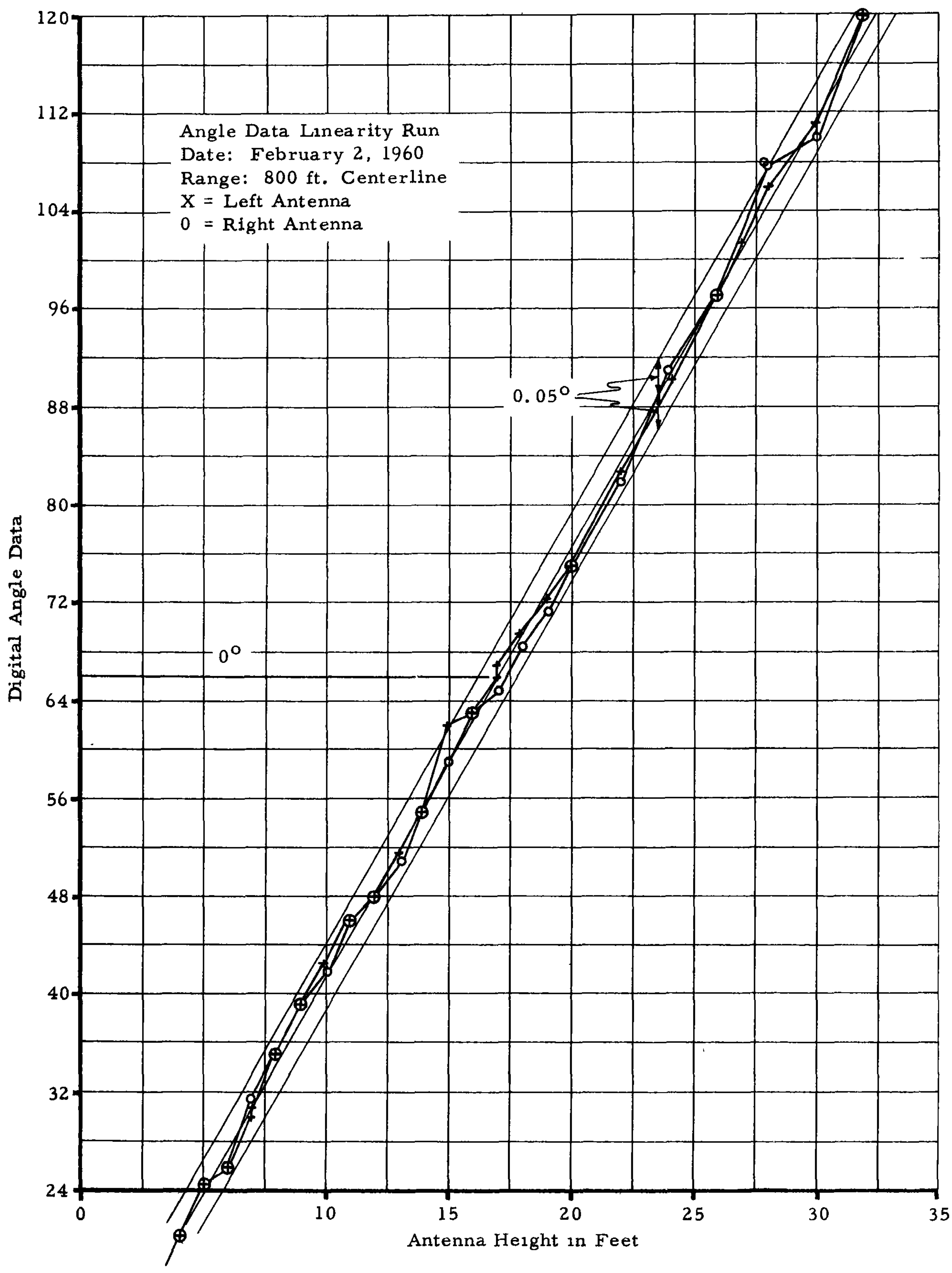


Figure 3-21. Angle Data Linearity Curve (Sheet 1 of 4)

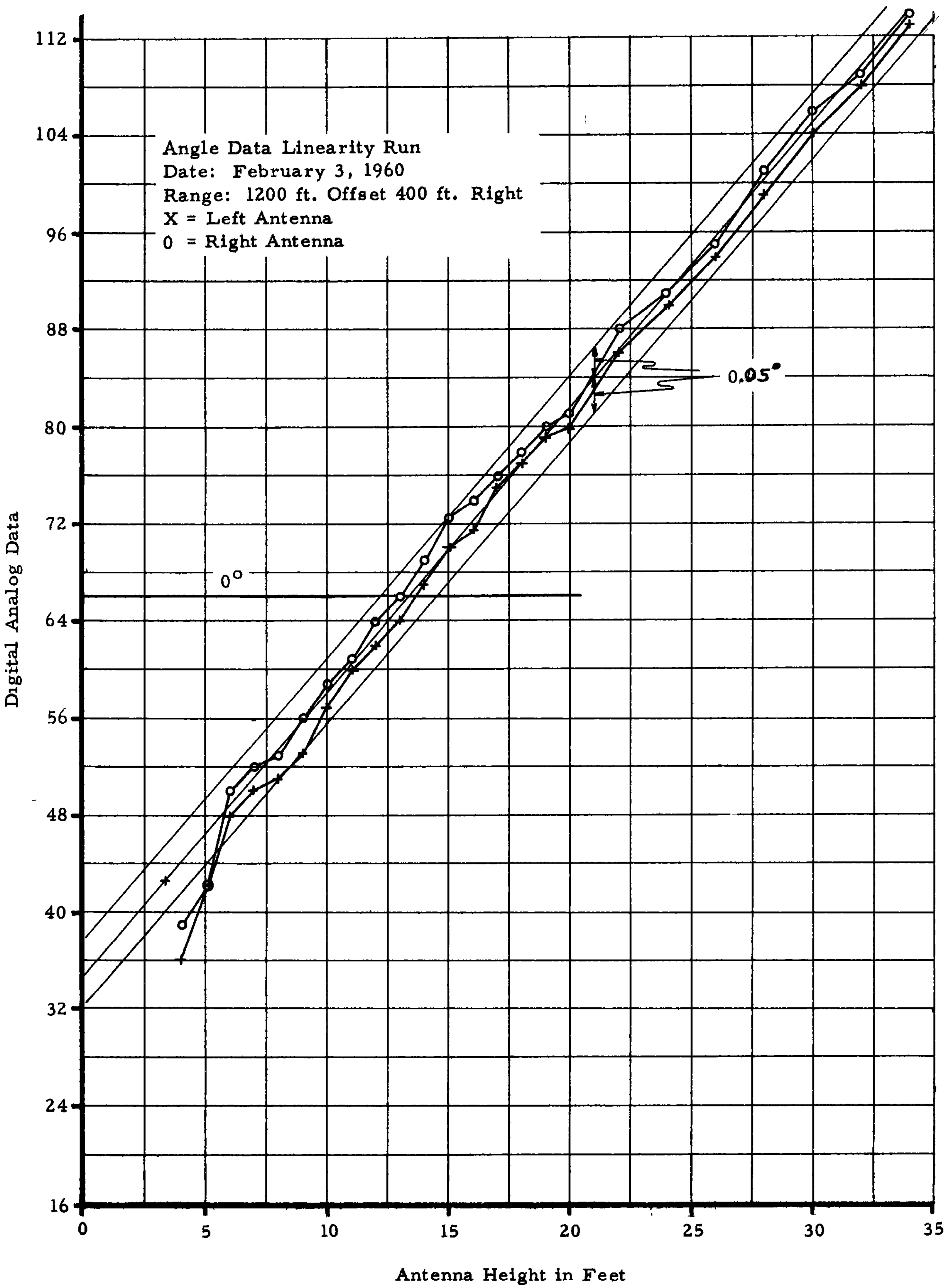


Figure 3-21. Angle Data Linearity Curve (Sheet 2 of 4)

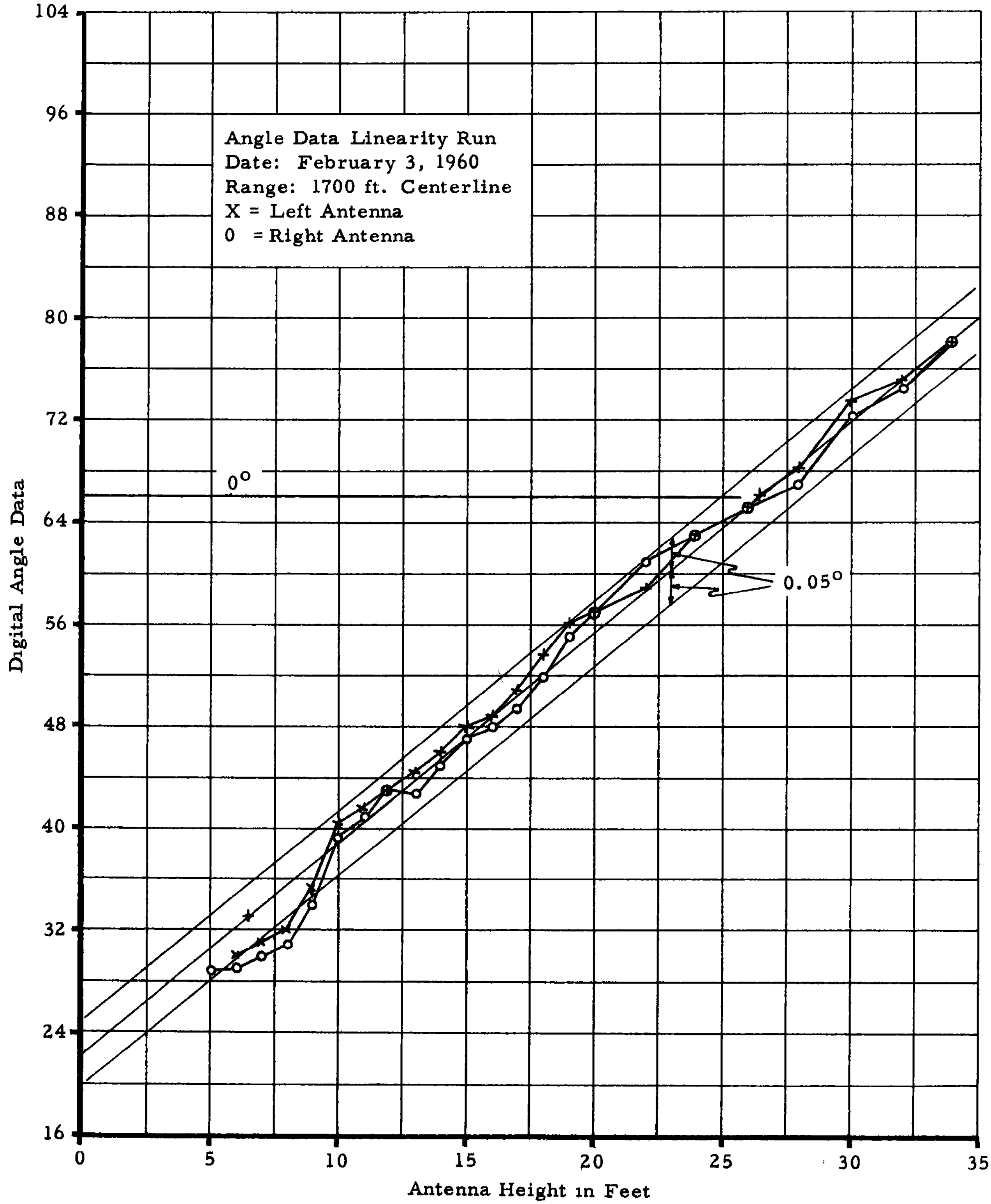


Figure 3-21. Angle Data Linearity Curve (Sheet 3 of 4)

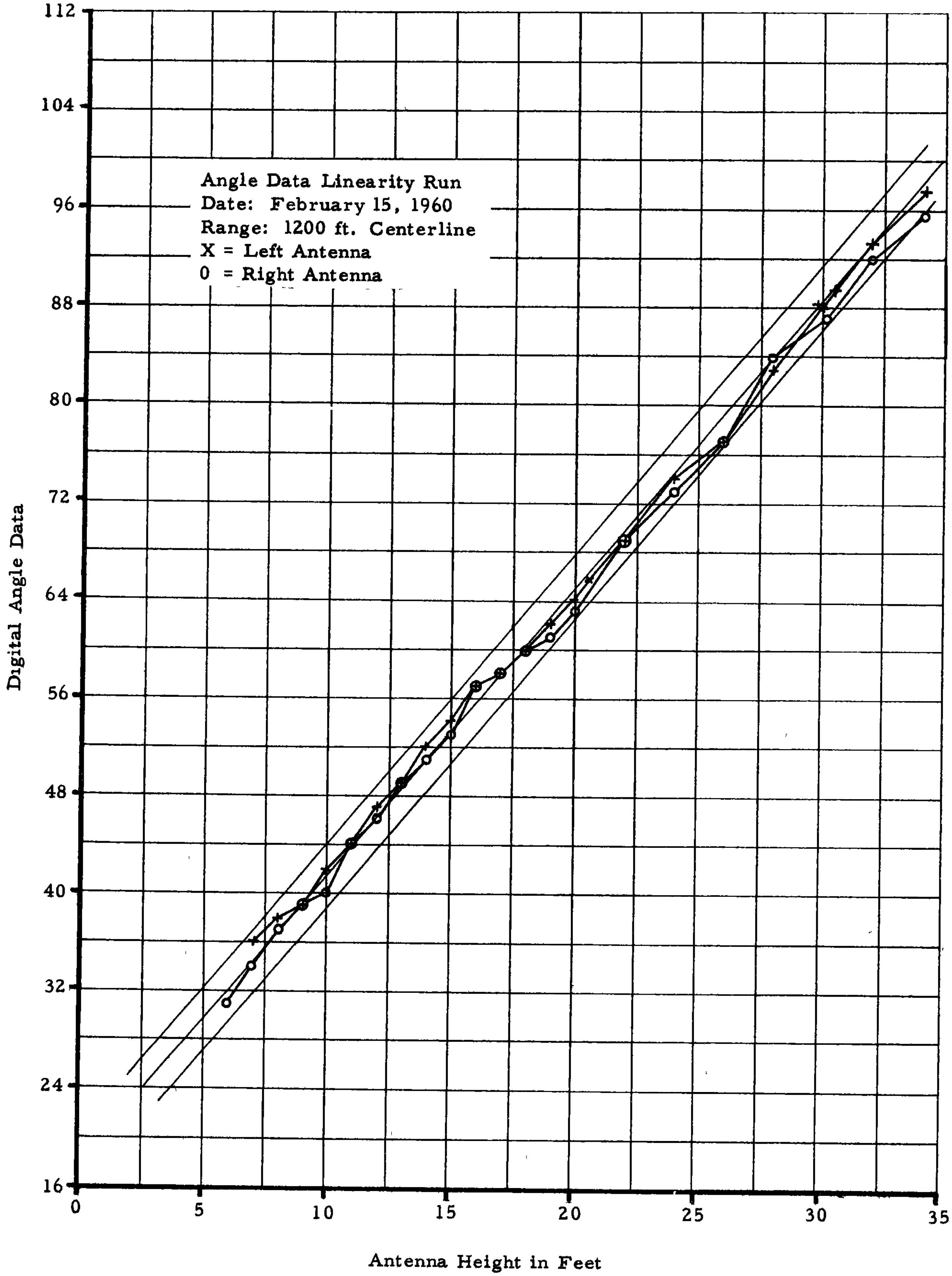


Figure 3-21. Angle Data Linearity Curve (Sheet 4 of 4)

ANGLE DATA LINEARITY TEST

Range: 1200' Offset: Centerline
Date: 15 February 1960 Time: 1630
Site elevation for zero degree or 66 bit count 20 feet 5 inches.
Site range, bits per foot: 2.3515
Notes: x = Points plotted on curves of Figure 3-21

Range Volts Tested = 0.379 volts

	Left Antenna Readout								Right Antenna Readout							
	128	64	32	16	8	4	2	1	128	64	32	16	8	4	2	1
34		x	x					x		x		x	x	x	x	x
32		x		x	x	x		x		x		x	x	x		
30		x		x	x					x		x		x	x	x
28		x		x			x	x		x		x		x		
26		x			x	x		x		x			x	x		x
24		x			x		x			x			x			x
22		x				x		x		x				x		x
20		x									x	x	x	x	x	x
19			x	x	x	x	x				x	x	x	x		x
18			x	x	x	x					x	x	x	x		
17			x	x	x		x				x	x	x		x	
16			x	x	x			x			x	x	x			x
15			x	x		x	x				x	x		x		x
14			x	x		x					x	x			x	x
13			x	x				x			x	x				x
12			x		x	x	x	x			x		x	x	x	
11			x		x	x					x		x	x		
10			x		x		x				x		x			
9			x			x	x	x			x			x	x	x
8			x			x	x				x			x		x
7			x			x					x				x	
6												x	x	x	x	x
5																
4																

Figure 3-22. Data Sheet, Angle Data Linearity Test

Sanborn recorder.) Over the zone of coverage within the above ranges, the average value of the range voltage was found to be within 18 millivolts (60 feet) of the theoretically calculated value. It was discovered, however, that the range measuring system exhibited track noise, which corresponded at times to a peak-to-peak variation of 100 to 150 feet. It is felt that the noise has been greatly reduced by a circuit modification made since the completion of the system tests.

3.2.5 Coverage Tests. - The coverage capability of the REGAL system was tested using an aircraft, which was equipped with a REGAL receiver, and which flew several different flight patterns over the REGAL ground equipment test installation. Angle data good and range data good signals were indicated by an ID-249 cross-pointer indicator installed in the aircraft. The results of the coverage tests are shown in Table 3-3.

TABLE 3-3

COVERAGE TEST DATA

Flight Pattern	Angle Data Good	Range Data Good
Inbound along centerline of REGAL ground equipment	14-1/2 n. mi.	10 n. mi.
Inbound 12 degrees left of REGAL ground equipment centerline	11-1/2 n. mi.	10 n. mi.
Inbound 12 degrees right of REGAL ground equipment centerline	11-1/2 n. mi.	10 n. mi.
Inbound 24 degrees right of REGAL ground equipment centerline	11 n. mi.	8.5 n. mi.
Inbound approximately 50^{o} right of centerline	3 n. mi.	Not recorded

3.2.6 Noise Test Analysis. - A sufficient number of tests were made to determine the approximate static noise characteristics of the REGAL system. A description of these tests and their analysis is included in Appendix A. The most significant results from the noise test analysis are as follows:

For a landing system with an equivalent cutoff frequency of 3 rad/sec,

a. The RMS error in altitude would be between 0.1 and 0.2 feet at a range of 1200 feet.

b. The RMS error in altitude rate would be between 0.15 and 0.35 feet/second at a range of 1200 feet.

The distribution of these altitude errors should be well approximated by the Rayleigh distribution. On this basis, the probability that the RMS value will be exceeded is about 0.35, and the probability that twice the RMS value will be exceeded is about 0.02.

3 rad/sec was chosen as the maximum cutoff frequency required for most practical landing systems. However, since most practical landing systems will have a cutoff frequency of less than 3 rad/sec, even smaller RMS errors can be expected.

3.2.7 Summary of Test Results. - The following paragraphs summarize the results from the angle accuracy tests, range accuracy tests and coverage tests.

3.2.7.1 Angle Accuracy Tests. - The contract calls for a positional accuracy "equivalent to at least 0.05 degrees" but not less than ±2 feet in the region of touchdown. Precise static accuracy measurements made at several locations in the touchdown region shows that the peak elevation angle error did not exceed 0.05 degrees, except at points below the minimum coverage described in paragraph 3.2.7.3. In every test performed, however, the 0.05-degree error represented less than a 2-foot error.

3.2.7.2 Range Accuracy Tests. - The contract specifies a range measurement accuracy of less than one per cent or less than ±50 feet, whichever is greater. In the static accuracy measurements made of the range data within the confines of the Gilfillan Airport at Fontana, the average value of the range output voltage was within 60 feet of the correct value. However, the range tracking noise was definitely higher than expected from the design and previous testing. The magnitude of the noise was less than 150 feet peak-to-peak. One probable cause for the range tracking noise was found and corrected, so the range tracking performance should be improved in the future.

3.2.7.3 Coverage Tests. - The contract requires that the equipment provide a range coverage of at least ±12 degrees. The coverage tests indicated that the equipment provided reliable angle data to a range of approximately 14 nautical miles along the equipment centerline and greater than 11 nautical miles at azimuth angles of 12 degrees from the equipment centerline. Since the range data system saturates at a range of 10 nautical miles, the performance figures for range data confirmed that reliable data was obtained at 10 nautical miles both on the equipment centerline and at 12 degrees off the centerline. Additional flight tests indicated that the equipment provided reliable range and angle data to a range of 10 nautical miles at 24 degrees off center and to approximately 3 nautical miles at 50 degrees off center.

The contract also calls for an elevation angle coverage of 1.5 degrees to 20 degrees. The REGAL equipment was designed for the antennas to scan from +20 degrees to -0.8 degrees. No instrumented measurements were made of the upper extreme of elevation angle coverage, but qualitative type tests indicated that reliable data is obtained up to approximately 20 degrees. It can be predicted from theory that the angle data reliability will deteriorate above approximately 19.6 degrees.

Precise tests of the minimum elevation angle coverage of the REGAL equipment were made at several locations in the touchdown region. These tests showed that reliable elevation angle data was obtained to -0.6 degrees with respect to the antenna scan axis but not lower than 0.28 degrees above the ground plane. This data was obtained with aircraft antenna heights of 6 feet above the ground at a range of 1200 feet from the transmitter and 8 feet above the ground at a range of 1700 feet.

3.3 Rapid-Scan Antenna

During the initial phases of the development program, consideration was given to the procurement of an inertialess or low-inertia antenna system. This antenna would be compatible with the REGAL system and would provide the capability to evaluate the REGAL techniques with scan rates of 10 or more scans per second. Specifications were drawn up and submitted to twelve companies having outstanding capabilities in the design of rapid-scan antennas. Detailed technical proposals were received from ten of these companies. In addition, oral presentations were made by four companies providing additional information on their proposed approach to the rapid-scan antenna. This section presents a brief description of the more attractive technical approaches, together with comments concerning the feasibility of each.

The specifications for the rapid-scan antenna called for performance essentially similar to that of the mechanically-scanned antenna fabricated for the REGAL equipment, with the exception of the scan rate. These specifications included:

Elevation Beamwidth (outside)	1.5° at 20 db below peaks
Azimuth	24° at -3 db
Side lobe level	-20 db
Scan range	$+20^{\circ}$ to -1.0°
Scan rate	10 scans/second

Due to the stringent antenna performance requirements, the best type of antenna for this system is not obvious. In evaluating these schemes particular attention was paid to the problems associated with design, fabrication, linearity and accuracy of data-take-off, and the expected performance. The principal features of the proposed antennas are described in the following paragraphs.

3.3.1 Constrained Metal-Plate Lens. - A unidimensional constrained metal-plate lens was proposed which is illuminated from a double horn through a parallel plate section. The parallel plate region, while maintaining a fixed spacing between the parallel plates, is bent and formed in such a fashion that at the feed end, the focal arc is on the arc of a circle of fairly small diameter. The feed horn can be rotated to follow this arc and feed the parallel plate region, thus causing the beam to scan. Since a 55 per cent dead time is desired, the focal arc can be 45 per cent of the circumference of a circle to give one scan per revolution of the feed horns.

The parallel plate section of this antenna would be rather large and cumbersome to manufacture and install, but it is not of a critical nature and should not present any large problems. The lens and feed assemblies are relatively straightforward and also should not present any large problems. The one disadvantage of the lens is that it may require a non-linear data-take-off device. Although this will require considerable calibration effort, it is not considered to be a severe limitation.

3.3.2 Foster Scanner. - A modified Foster Scanner was proposed to perform the elevation scan. The proposed scanner has the line-source feed in the inside of the rotor and rotating with it, in contrast to the conventional Foster scanner, where the line-source feed is outside the stator and is stationary. This modification results in a reduction in the complexity of the rotor design but does not require a higher rotor speed than the conventional Foster Scanner.

The line source feed would be a waveguide array which is center-fed to provide an elevation pattern whose main beam has a deep null. The beam shift with frequency can be compensated by pivoting the two halves of the array about the center. The output of the scanner would feed a reflector shaped to achieve the desired azimuth pattern.

Although it was considered feasible to design a Foster Scanner, there may be some performance limitations due to the mechanical problems. The Foster Scanner would not offer much area for future expansion, and it would be expensive to design the first model and to manufacture, install and maintain in production.

3.3.3 Luneberg Lens. - A Luneberg lens was proposed as the basic elevation beam-forming device. The variation in dielectric constant of the lens is achieved by the use of a dielectric material with varying dielectric constant. Actually, the variation of dielectric constant would be accomplished in a number of steps, say ten. A virtual source type of lens is formed by folding the lens in half. It would be impractical to form the interferometer type beam with a dual horn because of the wide angle illumination required. The split beam is formed by having half of the reflecting section displaced to realize a 180-degree phase reversal in half of the aperture distribution.

There are several disadvantages to the Luneberg lens, including the expected high dielectric losses, the side lobe problem, and the fabrication difficulties. In addition, a non-linear data take-off may be required with the attendant calibration problems.

3.3.4 Phase-Scanned Linear Array. - The principal feature of another antenna is a beam-scanning technique which uses a variation in the interelement phase-shift of a linear waveguide array. The varying phase-shift is obtained by varying the depth of insertion of dielectric plates into the waveguide. This is accomplished by a cam-driven reciprocating motion. There is some doubt that such a device can attain the required scan speeds for a reasonably long life and with sufficient accuracy. A second serious problem would be the power-handling capability.

3.3.5 Ferrite Phase-Scanned Linear Array. - A phase-scanned linear array antenna was proposed which utilizes a unique ferrite phase-shifter. A Fox phase-shifter using ferrites is driven by a rotating magnetic field similar to a four-pole rotating machine. The currents in the field coils of the phase shifters are of common amplitude but have a uniformly progressive frequency. These ferrite phase-shifters run in one direction only. A Reggia-Spencer type of ferrite phase-shifter is in series with alternate Fox units to provide a 90-degree fly-back each time a new scan cycle is to be initiated. This doubles the duty cycle of the antenna scan. Each radiating element would have its own phase-shifters. Perhaps 350 of these would be required.

This Fox ferrite-scan technique, although relatively untried, appears to have a very good possibility of readily satisfying the accuracy specifications. The array, the feed, and the phase-shifters would probably be smaller than in other proposed types. It would, however, require a moderately large amount of space and power for the phase-shift drivers.

3.3.6 Other Types of Scanners. - Several other types of rapid-scanning antennas were proposed which had severe limitations for the REGAL application and are mentioned briefly below.

a. A linear array, scanned by both a ferrite phase-shifter and a moving element in a trough waveguide, was proposed. This technique was mechanically complex and lacked the accuracy capability.

b. A circular reflector, illuminated by a set of rotating feed horns, was proposed. The large size (approximately 30 feet high) and the high center of rotation were severe limitations.

c. A specially contoured cylindrical lens, which rotated about a vertical linear array, was proposed. The inherent pattern distortions and fabrication problems were large disadvantages of this technique.

d. Ferrite phase-scanned linear arrays were also proposed, but there are very serious doubts about the accuracy and side-lobe levels attainable.

3.3.7 Conclusions. - The constrained metal-plate lens was considered to be the most suitable approach for the REGAL program for the following reasons:

a. Basically simple techniques.

b. Very good capability to meet accuracy and pattern requirements.

c. Capable of straightforward design and design changes.

d. Offered promise of completion within reasonable time and budget.

e. Sub-contractor capability and understanding of the problem.

The effort to procure an experimental rapid-scanning antenna for the REGAL equipment was discontinued after the proposal evaluation. This was due to the preliminary success with the mechanically-scanned array.

It should be fully appreciated that the development of a rapid-scanning antenna system, even on an experimental basis, will cost in the order of $200,000 and require approximately 18 months.

3.4 Coordinate Converter.

The coordinate converter unit (Figures 3-23 and 3-24) was developed to be used during the flight test program for the REGAL system. 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 an optimum unit for use in a final landing system. The coordinate converter was developed early in order to be available at an early date in the flight test program. At that time, the exact type of flight path computer to be used with the coordinate converter was not known. However, the flexible set of data outputs provided by the coordinate converter

Figure 3-23. Coordinate Coverter, Front View

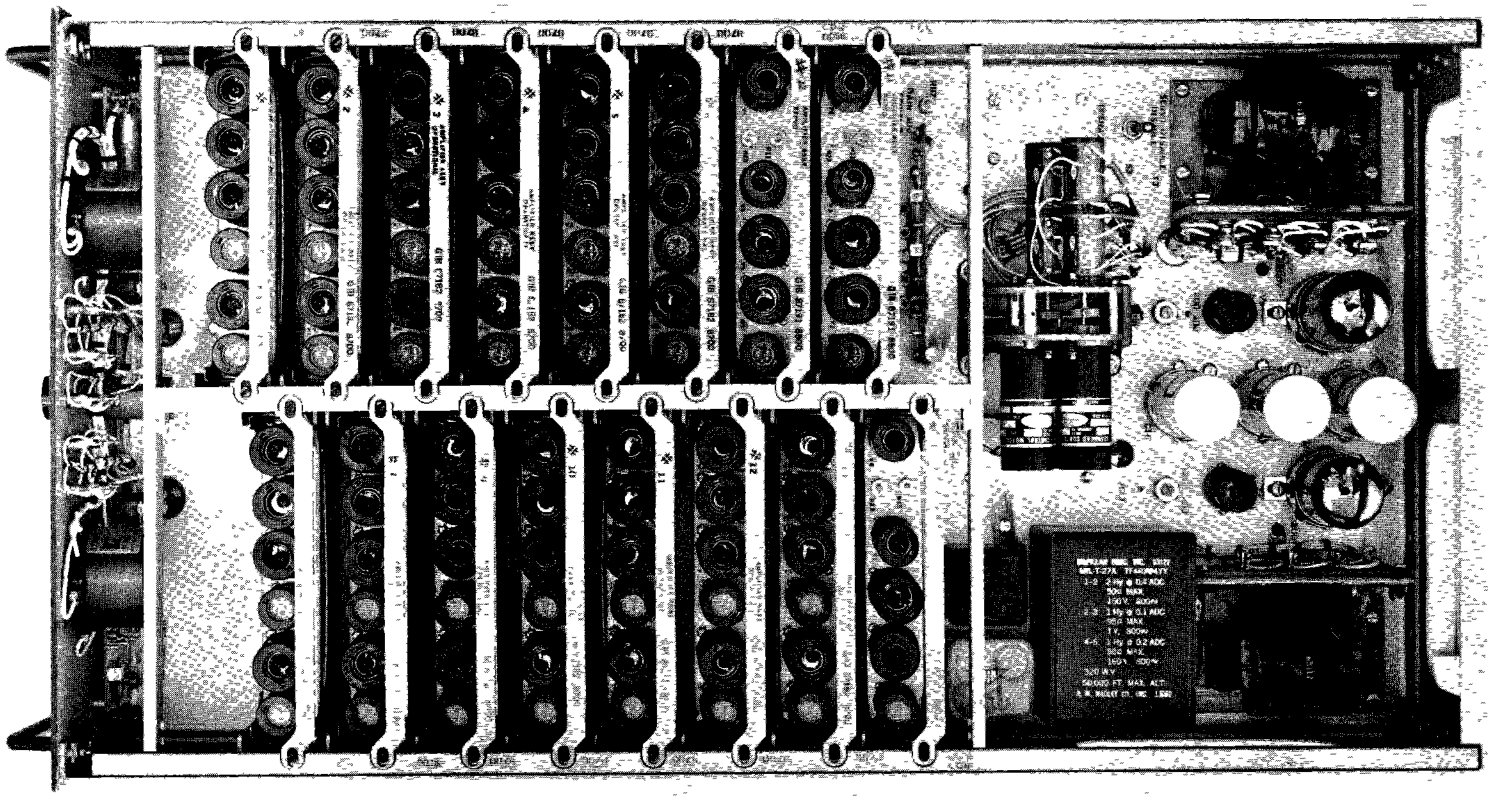


Figure 3-24. Coordinate Converter, Top View

will facilitate a variety of flight path computation techniques. Not all of the data outputs from the coordinate converter are necessary for flight path computation. Some of the outputs that are not required for flight path computation can be used for instrumentation or for instrument panel data.

The following paragraphs contain a detailed description of the function of the coordinate converter, input signals, output signals, controls, block-diagram theory of operation, and physical make-up.

3.4.1 Function. - The function of the coordinate converter is to solve the aircraft-approach plane trigonometric problem (diagramed in Figure 3-25) using analog computer techniques. The known parameters are Γ (radar elevation angle) and ρ (slant range). These are supplied to the coordinate converter by the REGAL airborne receiver. The range offset (d) is an arbitrarily selected ground plane distance from the radar site to the origin of transformed coordinates. The transformed coordinates are ρ_x and Γ_x. A straightforward trigonometric solution for ρ_x, Γ_x and h in terms of ρ, Γ, and d yields the following three equations:

$$\Gamma_x = \Gamma + \tan^{-1}\left[\frac{d \sin\Gamma}{\rho - d \cos\Gamma}\right]$$

$$\rho_x = \frac{\rho - d\cos\Gamma}{\cos(\Gamma_x - \Gamma)}$$

$$h = \rho \sin\Gamma .$$

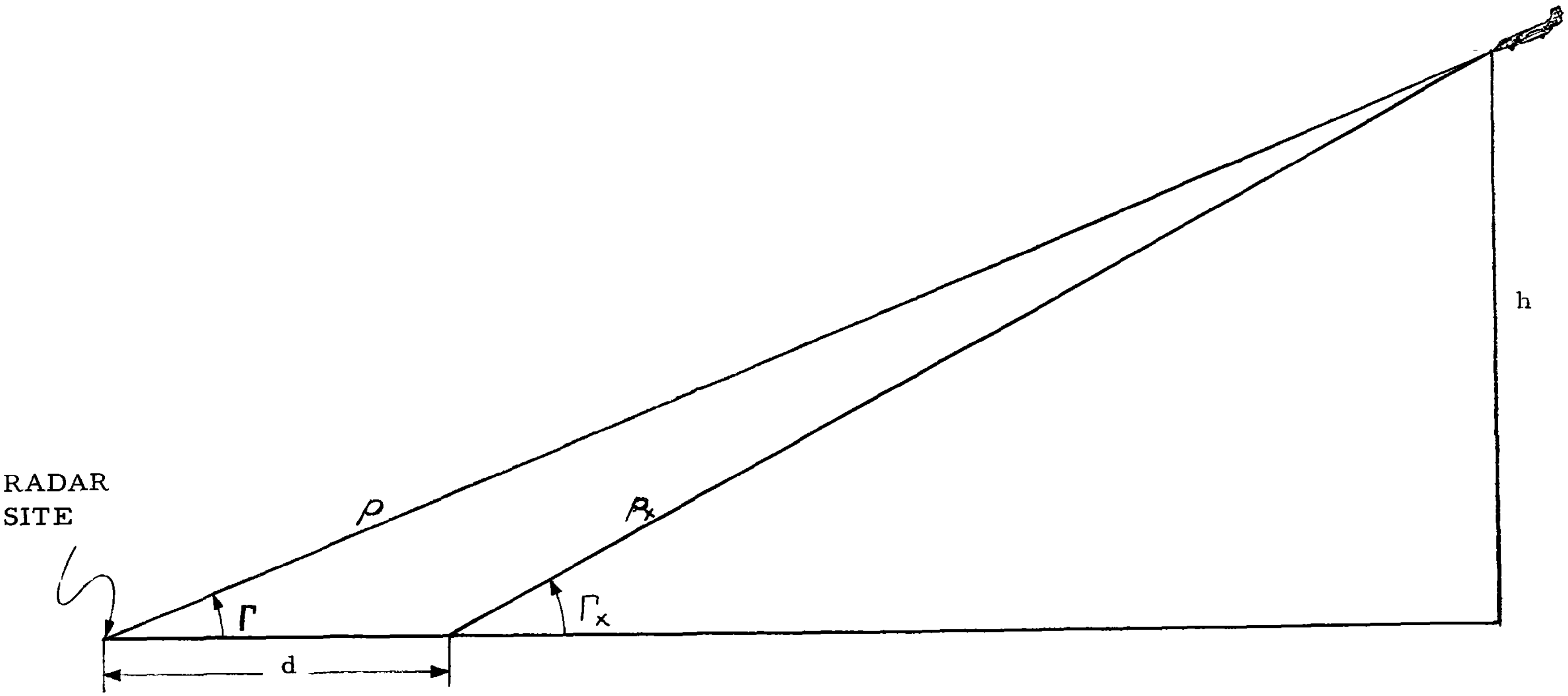


Figure 3-25. Trigonometry of Coordinate Transformation

In the approach problem, Γ and Γ_x are small angles. As a consequence, the small angle approximations of trigonometric functions may be applied.

The above equations reduce to:

$$\Gamma_x = \Gamma + \Gamma \frac{d}{\quad - d}$$

$$\rho_x = \rho - d$$

$$h = \rho \Gamma \; .$$

These are the equations that are mechanized by the coordinate converter.

An additional task performed by the coordinate converter is to extract the derivative of the input and transformed parameters.

3.4.2 Inputs. -The inputs to the coordinate converter come from the REGAL airborne receiver. These are: elevation angle (Γ); slant range (ρ); computer reference voltage, glideslope reference no. 1 (Γ_{GS} no. 1) and glideslope reference no. 2 (Γ_{GS} no. 2); range offset (d) or external range offset (d ext); and signal common.

All signal inputs are analog voltages with low source impedance (under 500 ohms maximum). The individual scale factors are: 0.9v/deg for Γ and Γ_{GS}, 1.8v/6000 ft for ρ, and 1.0v/6000 ft for d. The computer reference voltage is nominally 18.720v and is precision regulated to within 10 millivolts of nominal value.

3.4.3 Outputs. - The unit outputs are analog voltages which are tabulated in Table 3-4.

The output voltages are operational amplifier low impedance outputs (below 1 ohm). Special precautions should be taken to insure that overloading of output signals will not occur. Overloads can result in serious damage to the unit.

3.4.4 Controls. - The unit operational controls are all situated on the front panel. All other controls which are required for test and alignment purposes are internally located in the unit. The front panel controls are: GLIDE SLOPE SEL switch, RANGE OFFSET SEL switch, and RANGE OFFSET control.

The GLIDE SLOPE SEL is a toggle switch that enables the selection of a glideslope reference input to the unit from one of two external sources. The scale factor of these voltages is 0.9v/deg.

The RANGE OFFSET SEL switch enables the selection of either the internal range offset or a range offset voltage from an external source. The internal range offset voltage (d) is set by the RANGE OFFSET control dial. This dial is calibrated to read offset distance directly in thousands of feet and decimal fractions thereof. The useful range of the dial is 0 to 8000 feet, although it can be set to a maximum of 10,000 feet. The control is a 10-turn wire-wound potentiometer and the output scale factor is 1v/6000 feet.

TABLE 3-4

Coordinate Converter Output Voltages

Output Designation	Symbol	Scale Factor	Max Output	Max. Load
Elevation Angle	Γ	0.9v/deg	+18v	NA
Elevation Angle (Test Output)	$-\Gamma$	-1.0v/deg	NA	NA
Elevation Angle Rate	$\dot{\Gamma}$	25v/deg/sec	$\pm$100v	2 ma
Glideslope	Γ_x	5.0v/deg	$\pm$100v	5 ma
Glideslope Rate	$\dot{\Gamma}_x$	25v/deg/sec	$\pm$100v	2 ma
Glideslope Error	$\Delta\Gamma$	10v/deg	$\pm$50v	10 ma
Range	ρ	1.8v/6000 ft	+18v	NA
Range Rate	$\dot{\rho}$	25v/1000 ft/sec	$\pm$100v	2 ma
Converted Range	ρ_x	1v/3000 ft	+20v	5 ma
Converted Range Rate	$\dot{\rho}_x$	25v/1000 ft/sec	$\pm$100v	5 ma
Coarse Altitude	h_c	0.04v/ft	+100v	5 ma
Fine Altitude	h_f	0.4v/ft	+100v	5 ma
Precision Reference	18.720v	--	--	--
+200v (Test Output)	--	--	--	--
-200v (Test Output)	--	--	--	--
Power Supply Comm	--	--	--	--

On the backside of the front panel is located the range offset trim potentiometer that is used to calibrate the RANGE OFFSET control at the 8000-foot dial setting.

On the underside of the unit chassis are located the zero set adjustment potentiometers used in nulling the position voltage outputs of the unit. No null adjustments are provided for the rate voltage outputs. As a consequence, zero set controls are used only for amplifiers no. 1, no. 3, no. 6, no. 8, no. 12, and no. 13. Each zero set control is mounted on the terminal board corresponding to the operational amplifier it is used with. These should be aligned using unit bench test fixture and test procedure. Under normal operating conditions, alignment should not be required except at infrequent intervals.

There are two controls on each servo amplifier module; these are labeled R11 and R23. These controls are locked settings for adjusting voltage feedback from the servo motor, and for balancing the current in the output tubes, respectively. Neither control normally requires readustment. In particular, for best stability of operation, R11 should always be maintained in the maximum ccw position. The gain control for each servo channel is located external to the amplifier module. For servo no. 1, the gain is self-controlled; the third section of the servo no. 1 pot assembly is used. The other two servo units have their gain controls located on the chassis deck, aft of the plug-in modules. Each control is properly labeled and the setting is locked. Under normal operating conditions, no readjustment should ever be required.

Aft of the servo motor and potentiometer assembly is located a chassis-mounted toggle switch labeled SERVO DISABLE. This switch is normally maintained in the OPERATE position. Its function is to disengage the servo potentiometers from all data inputs. It is used only in the bench test and alignment of the unit.

The power supply voltage regulator controls are located on the rear section of the chassis main deck.

3.4.5 Block Diagram. - Figure 3-26 is a functional block diagram of the coordinate converter. For purpose of clarity, only the computing, switching, and limiting elements are shown. Transfer impedances are used rather than actual parameter values in an effort to simplify to bare essentials.

It is to be noted that the computer may be essentially divided into three basic processes. The first process involves Γ , the extraction of its derivative, its coordinate transformation, error calculation, and transformed derivative. These tasks are performed by operational amplifiers no. 1 through no. 6 and servo no. 1.

The second process involves ρ , the extraction of its derivative, coordinate transformation, and extraction of its transformed derivative. These tasks are performed by operational amplifiers no. 7 through no. 11.

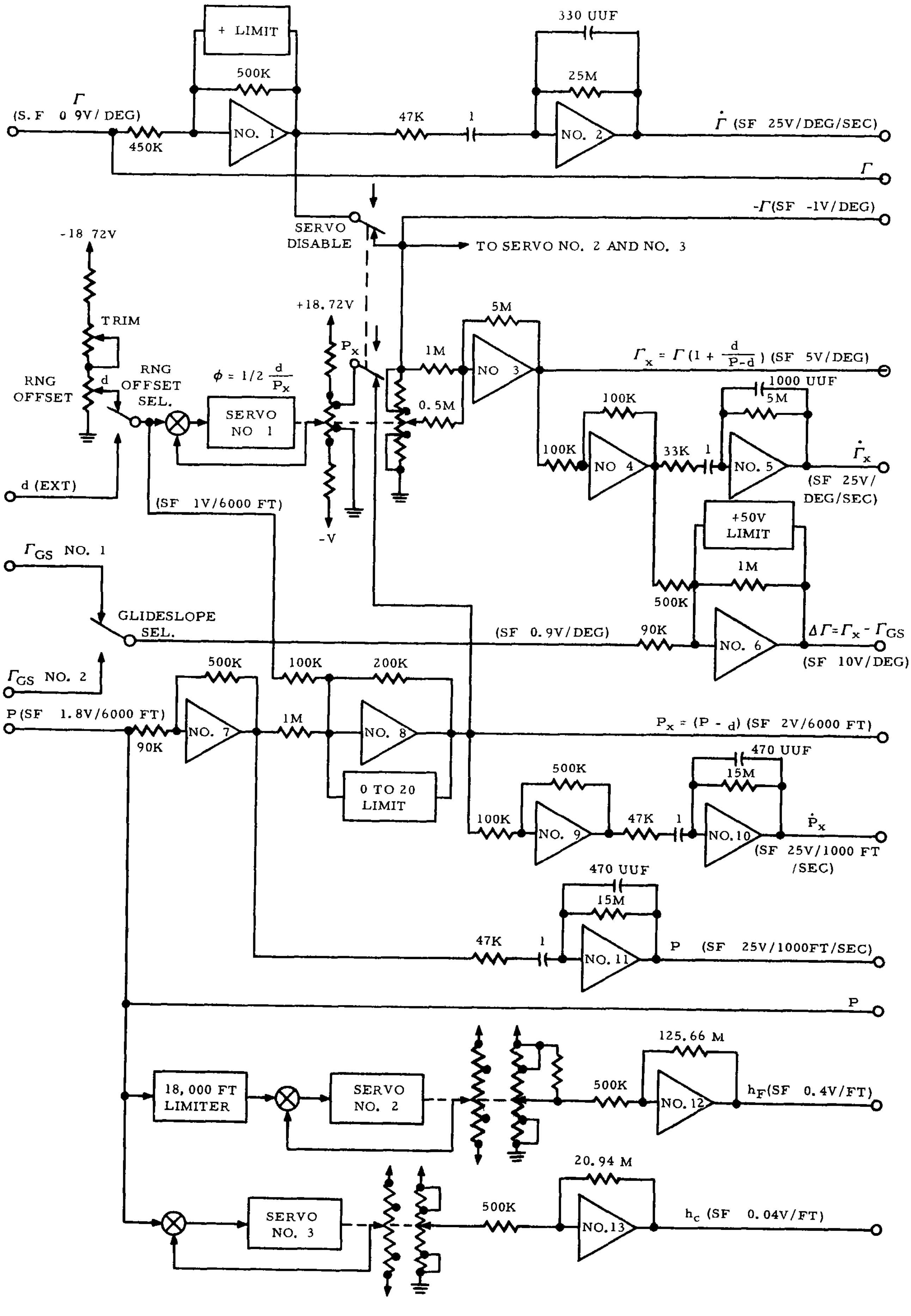


Figure 3-26. Coordinate Converter Block Diagram

The third process is altitude computation, both coarse and fine. This task is performed by servos no. 2 and no. 3, and operational amplifiers no. 12 and no. 13.

The above-mentioned tasks are described in further detail in the following paragraphs of this report.

3.4.5.1 Elevation Angle Computations. - The input Γ (scale factor 0.9v/deg.) signal is accepted by amplifier no. 1, an inverting amplifier with a gain of 1.111. The output of amplifier no. 1 is $-\Gamma$ with a scale factor of 1.0v/deg. The output signal passes directly to amplifier no. 2 which extracts the derivative of $-\Gamma$ with a gain of 25. The output is $\dot{\Gamma}$ with a scale factor of 25v/deg./sec.

The $-\Gamma$ output of amplifier no. 1 is also applied to a computing potentiometer on each of the three servos. The computing potentiometer of servo no. 1 is a servo multiplier potentiometer that multiplies the shaft position ($\emptyset$) with $-\Gamma$. The shaft position ($\emptyset$) is a function of d (range offset) divided by ρ_x (converted range). The output voltage of the potentiometer is, thus, $-\Gamma\emptyset$. Operational amplifier no. 3 sums $-\Gamma\emptyset$ with $-\Gamma$ to generate the function Γ_x (glideslope angle).

It is recalled that,

$$\Gamma_x = \Gamma + \Gamma \frac{d}{\rho - d} = \Gamma + \Gamma \frac{d}{\rho_x}$$

is the synthesis equation for glideslope angle. The Γ_x scale factor is 5v/deg.

Servo no. 1 is, as has been mentioned, a dividing servo. The voltage d (range offset), from either the internal or external selected source, is applied to the input of the servo. The converted range voltage (ρ_x), which is equal to

$$\rho_x = \rho - d$$

is applied to the servo feedback potentiometer. By servo position nulling action, the servo shaft assumes position,

$$\phi = \frac{d}{\rho_x} .$$

The shaft position angle is used to assist in mechanizing the equation for Γ_x.

Γ_x, the output of operational amplifier no. 3, is applied to operational amplifier no. 4, a unity inverter. The output of amplifier no. 4 is $-\Gamma_x$, which is applied to amplifiers no. 5 and no. 6. Amplifier no. 5 extracts the derivative, $\dot{\Gamma}_x$, with a gain of 5. The $\dot{\Gamma}_x$ output scale factor of amplifier no. 5 is 25v/deg./sec.

Amplifier no. 6 sums $-\Gamma_x$ with a Γ_{GS} input. The output of amplifier no. 6 is the glideslope error function $\Delta\Gamma$, whose equation is:

$$\Delta\Gamma = \Gamma_x - \Gamma_{GS}.$$

The gain of amplifier no. 6 is chosen so that the $\Delta\Gamma$ scale factor is 10v/deg. A 50-volt diode limit circuit limits the maximum positive $\Delta\Gamma$ output to approximately 50 volts.

Operational amplifier no. 1 also has a diode limit circuit, the purpose of which is to prevent the output of the amplifier from ever going positive. Under normal operating conditions, a positive output is never encountered. This is tantamount to elevation angles below ground. If, however, an erroneous Γ input or a system malfunction should occur which tends to make the $-\Gamma$ voltage positive, servo damage might occur. The diode limiter offers protection against this type of occurence.

3.4.5.2 Range Computations. - The unit range voltage input (ρ), with a scale factor of 1.8v/6000 ft, is applied to operational amplifier no. 7, an inverting amplifier with a gain of 5.555. The output is $-\rho$, with a scale factor of 10v/6000 ft, which is applied to operational amplifiers no. 8 and no. 11. Amplifier no. 8 sums $-\rho$ with d to generate the function, ρ_x, which is defined as,

$$\rho_x = \rho - d$$

The scale factor of ρ_x is 2v/6000 ft. Amplifier no. 11 takes the derivative of $-\rho$ with a gain of 15. The output of amplifier no. 11 is $\dot{\rho}$ with a scale factor of 25v/1000 ft/sec.

The ρ_x output of amplifier no. 8 is inverted and amplified by amplifier no. 9. The output scale factor of amplifer no. 9 is 10v/6000 feet. Amplifier no. 10 then takes the derivative of the $-\rho_x$ output of amplifier no. 9. The differentiator gain is 15. The output is ρ_x with a scale factor of 25v/1000 ft/sec.

3.4.5.3 Altitude Computations. - The coordinate converter performs a coarse and a fine altitude computation. The coarse altitude (h_c) computer computes altitude for all ranges to a maximum height of 2500 feet with a scale factor of 0.04v/ft. The fine altitude (h_f) computer duplicates the action of the coarse computer with the exception that it is range limited to 18,000 feet, and the maximum altitude capability is 250 feet. The fine altitude scale factor is 0.4v/ft. In both cases, the equation mechanized is:

$$h = \rho \Gamma .$$

The product mechanization is accomplished by servo multiplication of range and elevation angle. Range voltage is converted to a servo shaft position, which is applied to operate a potentiometer energized by $-\Gamma$. The output voltage is thus the product term $-\rho\Gamma$. An operational amplifier is used to invert the product and adjust the scale factor to the desired value.

The fine altitude computer uses servo no. 2 to perform the required servo multiplication. The maximum range tracking capability is 18,000 feet. A ρ limit circuit protects the servo from range inputs in excess of 18,000 feet.

The servo multiplier output of servo no. 2 is inverted and amplified by operational amplifier no. 12. The operational amplifier provides a gain of 251.3 and the required polarity inversion so that h_f has a scale factor of 0.4v/ft.

The coarse altitude computer uses servo no. 3 for servo multiplication of ρ and $-\Gamma$. This servo is capable of tracking all ρ inputs to maximum system capability (60, 000 feet). Operational amplifier no. 13 supplies the necessary gain of 41.88 and the polarity inversion so that h_c has a scale factor of 0.04v/ft.

3.4.6 Physical Description. - The coordinate converter unit consists 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. For optimum tube life, however, it is recommended that removal and insertion of amplifiers be performed with power off.

The three servo amplifiers are wired-circuit plug-in modules. These units are also interchangeable. The receptacles and connectors for the servo amplifiers are pin-type. It is impossible, therefore, to mistakenly interchange a servo amplifier with an operational amplifier.

The servo motor and potentiometer assembly are mounted on a supporting bracket located on the rear section of the main deck. The servo motor terminal board and reference phase shift capacitors are located directly below the motor assembly on the underside of the chassis deck. The servo amplifier output transformers are also mounted on the underside of the chassis.

The power supplies and associated transformers, rectifiers, filters and regulators occupy the extreme rear of the unit.

On the front panel are mounted the blower fans, important test points, operating controls and indicating fuse holders. The controls are fully described in paragraph 3.4.4 of this report. On the backside of the panel are mounted the blower motor capacitors, and a circuit board containing the range offset trim circuit and the 18,000-foot limiter circuit.

On the front panel are also located all the connector receptacles of the unit. The receptacles mate to quick-release type, snap-twist connectors. The receptacles are labeled J91001, J91002, and J91003. Of these, J91001 is the input connector; J91002 is the power connector; and J91003 contains all unit outputs.

4. CONCLUSIONS

This final report has presented the technical data derived during the design and preliminary system testing of the REGAL equipment. It therefore contains a series of preliminary results and technical comments, and a discussion of ancillary technical effort undertaken during the design program.

4.1 Conclusions on System Design

Technical conclusions arrived at during the equipment design are presented here as a reference for further system evaluation and design.

4.1.1 Antenna System. - The mechanically-scanned linear-array antenna designed for the REGAL equipment has proven to be very satisfactory. The success of this antenna system makes it appear very practical to use a mechanically-scanned antenna for at least the early phases of system evaluation and utilization. The use of the mechanically-scanned antenna system will offer substantial monetary savings during the forthcoming steps in the overall development program, and at the same time, allow for an advancement in the state of the art of inertialess scanning antennas. The mechanical-scan technique is probably satisfactory up to scan rates of approximately 5 to 7 scans per second for a 16-foot linear array.

4.1.2 Coding System. - The digital data coding system employed in the REGAL equipment was adopted to fulfill the requirements of the experimental test program. This technique has proved very practical and reliable, but it has imposed requirements for additional size and complexity in both the ground transmitting equipment and the airborne receiving unit. After the basic principles of the REGAL system have been verified, after the exact requirements for data transmission for an operational landing system are more fully defined, and when more time and money are allowed for the development of system hardware, it will be entirely practical to adopt a simpler coding system. Several coding techniques have been suggested, based on the analog principle, which do not require the capability to produce 7-pulse code groups in the ground transmitting equipment, and which do not require the large number of components necessary to handle 10-bit digital data in the airborne receiver.

4.1.3 Data Take-off Technique. - Two techniques were tried for acomplishing precision data take-off from a mechanically-scanned antenna: the magnetic technique and the optical technique. Although both these techniques are capable of performing the required function, we believe the optical technique offers more flexibility and will be generally more satisfactory for a future system. Since these techniques were applied to a mechanically-scanned antenna, there was no problem of matching the linearity of the antenna scan to the linearity of the data take-off equipment. If an antenna system with a non-linear relationship between the beam angle and the available shaft position were adopted, considerable complexity would be added to the data take-off problem. The non-linear data take-off problem can be solved by means of a customer-calibrated mechanism. Considerable time and money would have to be expended to arrive at a suitable calibration technique for production.

4.1.4 Airborne Receiving System. - The crystal-video receiver employed in the REGAL airborne unit has proved to be satisfactory even though its sensitivity is a little below expectations. As discussed in section 3.1.5, it is believed that a superheterodyne receiver would be more satisfactory for many types of airborne installations. If the final operational REGAL system were to operate at a higher frequency, e.g., at 16,000 megacycles, the use of a superheterodyne receiver would be mandatory for almost all types of aircraft installations.

4.1.5 Range-Tracking Technique. - The range-measuring system incorporated in the present REGAL equipment has come close to satisfying the specification requirements. It is believed that the REGAL equipment has demonstrated the feasibility of an accurate DME system incorporated in a small airborne unit; however, it is felt that the exact quantitative performance achieved in the REGAL equipment is not fully representative of the current state of the art. There are definite areas where the accuracy and stability of the airborne range tracker can be improved through further design effort.

4.2 Conclusions on System Performance

In section 3.2 the results of preliminary field testing are presented and the system performance is summarized.

In preliminary testing the angle measurement system was shown to be accurate to within 0.05 degrees with a minimum elevation coverage of 0.28 degrees above the ground plane. The range measurement accuracy is expected to be one per cent of the aircraft range but not less than 100 feet.

Final conclusions concerning system performance should be deferred until the results of the tests to be conducted at NAFEC become available.

In summary, it is believed that the delivered REGAL equipment meets the requirements of the specification except the minimum-range tracking-accuracy requirement. One area, where the REGAL equipment possibly falls short of the desired system performance, is in the amount of noise present in the REGAL angle output data. Although the specification did not explicitly cover the noise requirements of the system, careful examination of this subject should be made during the flight test program.

APPENDIX A

REGAL NOISE ANALYSIS

1. DEFINITION OF THE PROBLEM

The ultimate success of any aircraft landing control system depends upon the information that is derivable from continuous position information such as that to be provided by the REGAL system. In particular, successful de-crabbing just prior to touchdown and acceptable impact velocities require accurate altitude and altitude rate information. Noise characteristics of the REGAL system have been interpreted entirely in terms of the primary position data that is made available to the aircraft.

In terms of primary data, the altitude information that REGAL provides the aircraft can be approximated by

$$h = \rho\Gamma$$

where h = altitude of the aircraft in feet

ρ = range of the aircraft from the REGAL ground site in feet

Γ = angle of the aircraft with respect to the REGAL ground measured from the horizontal in radians.

If ρ and Γ are in error by the quantities $\Delta\rho$ and $\Delta\Gamma$, then the resulting altitude error is

$$\Delta h = \rho\Delta\Gamma + \Gamma\Delta\rho + \Delta\rho\Delta\Gamma$$

Thus far, ρ and Γ have been regarded as continuous functions. However, REGAL is intrinsically a sampled-data system, and some means must be provided to reconstruct the continuous functions from which the samples were derived if subsequent operations are to use analog techniques. As presently instrumented, Γ and ρ are reconstructed from discrete samples, which occur at a rate of five per second, ρ by means of a zero-order data hold or clamped sampler, and Γ by a range tracker with a large velocity-error coefficient. Therefore, $\Delta \rho$ and $\Delta \Gamma$ must represent the combination of those errors, or noise, in the discrete samples and those introduced in the process of reconstructing continuous functions.

In the case of ρ, even if the aircraft were subjected to tight control in range, the dynamic capabilities of conventional aircraft are relatively restricted. On this basis, $\Delta \rho$ can be made small by conventional and reasonable design of the range tracker, and the last two terms of the equation for Δh can be neglected. The remaining term, $\rho \Delta \Gamma$, however, will almost certainly appear as the primary variable in the elevation guidance loop. That is, the equipment associated with the reconstruction of Γ, to be referred to here as the Γ filter, will be essentially in series with the elevation guidance loop.

The performance capability of REGAL as employed in the elevation guidance loop of an automatic landing system can then be evaluated in the following three steps:

a. Determine the noise characteristics of Γ in a form suitable for further analysis (power spectra).

b. Determine a suitable Γ filter based on meeting the following requirements:

   (1) The output of the Γ filter should be in a form suitable for further analog processing, particularly differentiation.

   (2) The stability of the elevation guidance loop should not be significantly degraded by the Γ filter.

   (3) The accuracy of the elevation guidance loop should not be significantly degraded by the Γ filter.

c. Determine the expected errors in altitude and altitude rate based on a. and b.

2. THE NOISE CHARACTERISTICS OF Γ (ELEVATION ANGLE)

The following conditions applied to the measurement and reduction of the noise data:

a. The receiver was static for any particular data run.

b. The factor Γ was processed by receiver #1, which provides a clamped sample output.

c. DC drift in the output was not included.

Dynamic noise would include the effects of varying signal strength, nonlinearity of the average value of Γ , and tracking noise consisting of a 5-cps fundamental and higher harmonics.

The method used to determine the power spectra of $\Delta\Gamma$ consists of treating $\Delta\Gamma$ as a periodic phenomenon. This method is valid if the period of $\Delta\Gamma$ chosen is significantly longer than any of the system time constants. In all cases the recording of $\Delta\Gamma$ chosen for analysis were of a duration or period of about 55 seconds. On this basis the method is valid.

The data runs that have been analyzed are listed in the following table of particulars:

Run No.	Range (ρ) in feet	Lateral Offset	Altitude in feet	Date Recorded
Γ-1	1200	0	4.5	12/18/59
Γ-2	1200	0	8	1/26/60
Γ-3	1200	0	16	1/26/60
Γ-4	1200	0	28	1/26/60

The analysis of each run resulted in the following functions:

Function No.	Independent Variable	Dependent Variable	Comments
F-1	ω in rad/sec	Γ noise power in deg^2	Line Power Spectra
F-2	ω in rad/sec	Γ noise power density in deg^2/rad/sec	Approximate Continuous Power Spectra
F-3	ω_c in rad/sec	RMS altitude error in ft	System Accuracy Characteristics (F-3 through F-6, bracketed)
F-4	ω_c in rad/sec	RMS altitude rate error in ft/sec	
F-5	ω_c in rad/sec	Peak altitude error in ft	
F-6	ω_c in rad/sec	Peak altitude rate error in ft/sec	

Before these results are presented, the Γ filter will be considered.

3. THE DESIGN OF THE Γ FILTER

The argument leading to the need for the Γ filter is summarized:

a. REGAL is a sampled-data position measuring system.

b. REGAL data is to be used in automatic landing systems of which some are certain to be of the analog type.

c. REGAL sampled-data must therefore be reconstructed to continuous form to be compatible with subsequent analog operations, such as continuous differentiation.

d. The Γ filter is the device that reconstructs the Γ data.

The output of the Γ filter will be in a form suitable for continuous differentiation only if it is relatively free of discontinuities and the principal scan noise components that occur at 15.7 and 31.4 rad/sec. This requirement can probably be met if the attenuation of the Γ filter is at least 18 db at and above 15.7 rad/sec.

The stability of the elevation guidance loop can be adversely affected by both the phase and amplitude characteristics of the Γ filter. The phase lag contributed by the Γ filter in the neighborhood of the frequency corresponding to 0-db loop gain must not cut too deeply into the system phase margin. In a similar manner, the amplitude characteristics of the Γ filter must not introduce objectionable variations in either gain or gain slope over the same range of frequencies. These requirements can probably be met if, over a frequency range from 0 to 3 rad/sec, the phase lag is not greater than 15 degrees, the amplitude variations do not exceed ± 3 db, and the amplitude slope does not exceed ± 2 db/octave. The figure 3 rad/sec was chosen as the maximum cut-off frequency required for the most practical landing systems.

The above requirements are summarized graphically in Figure 1.

The basic configurations of the Γ filter which have been considered fall into the following categories: (1) clamped sampler; (2) clamped sampler followed by linear continuous filter; and (3) polynomial extrapolating sampled-data filter.

Although the amplitude response of the clamped sampler at the fundamental frequency meets the requirements of the Γ filter, it fails in the areas of compatibility and phase response. The output contains both discontinuities and strong scan-noise components. The phase angle $\theta_c = -0.1\omega$ radians and, for $\omega = 3$ rad/sec, the phase lag is 17.2 degrees.

Because of the basic simplicity of the clamped sampler as a data reconstruction device, it is highly desirable to use it if its deficiencies can be overcome or compensated for. Therefore, an attempt has been made to synthesize a relatively simple continuous linear filter so, that if preceded by a clamped sampler, the composite results would be acceptable.

The pole-zero plot of the best attempt to date at synthesizing a compensation filter for the clamped sampler is shown in Figure 2. The composite amplitude-phase response is shown in Figure 3. Although some of the requirements of the Γ filter are exceeded, the compatibility and scan noise suppression requirements would probably be met on a practical basis. This compen-

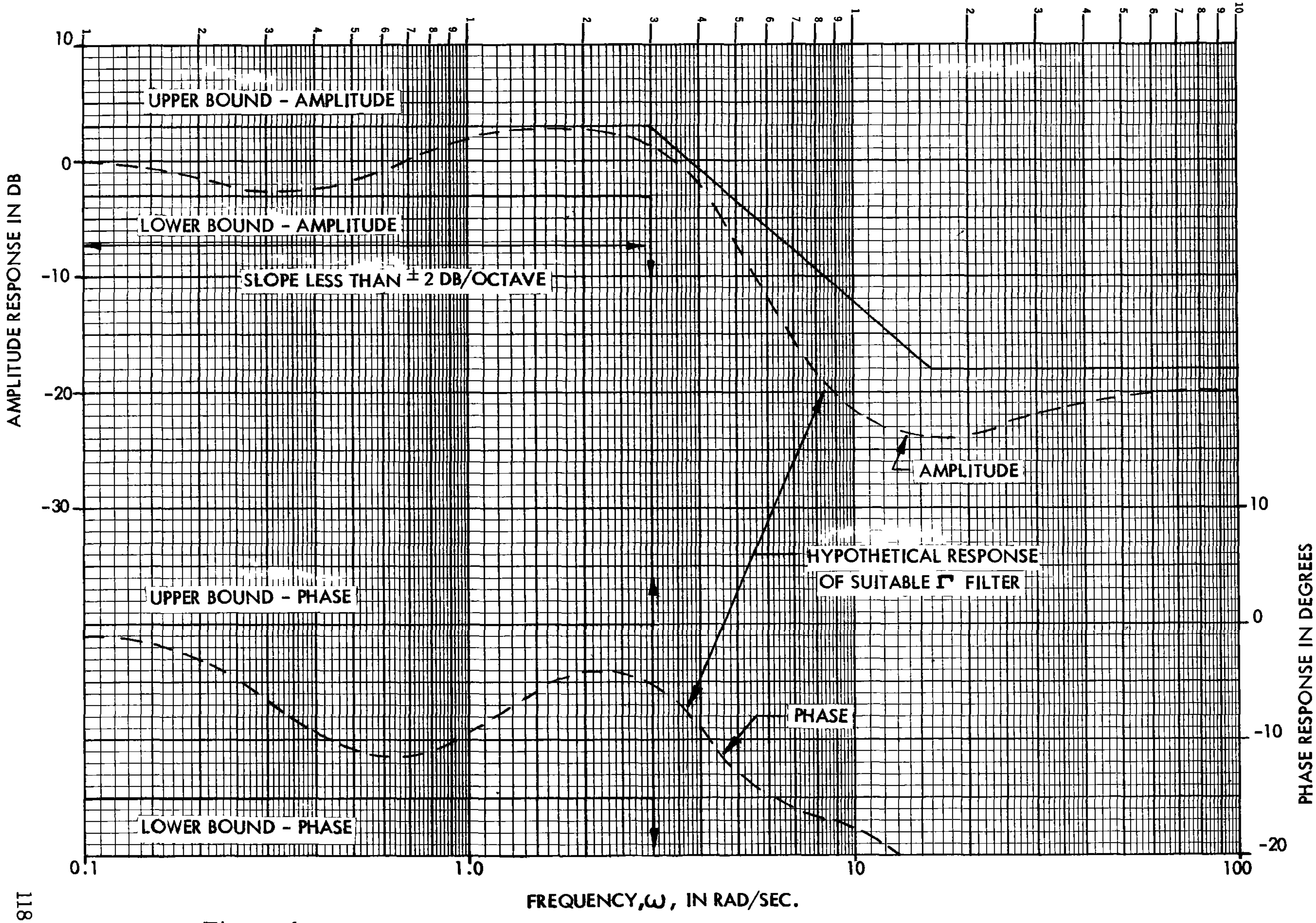
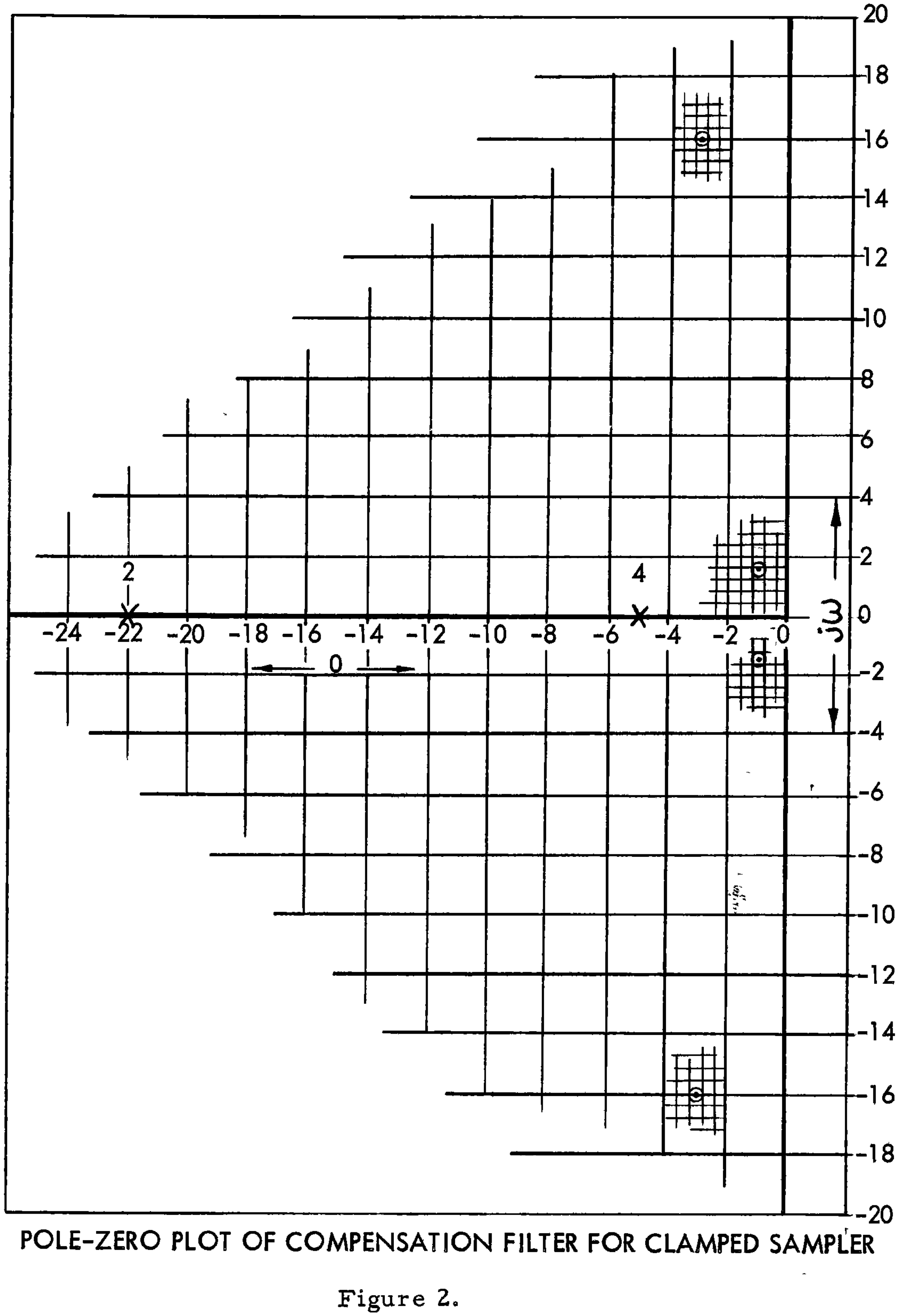


Figure 1. Frequency Response Requirements of Γ Filter



POLE-ZERO PLOT OF COMPENSATION FILTER FOR CLAMPED SAMPLER

Figure 2.

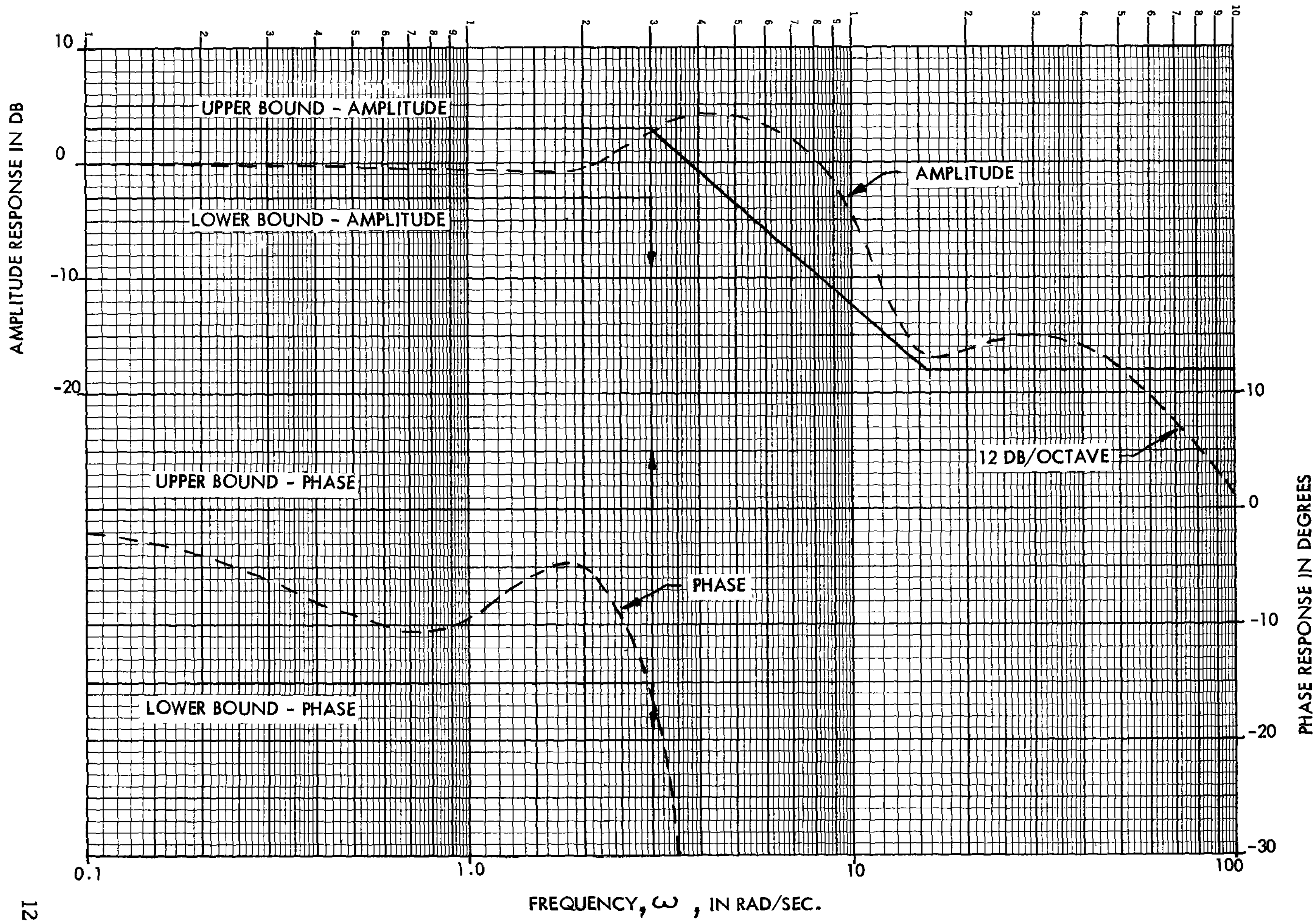


Figure 3. Frequency Response of Clamped Sampler with Compensation Filter

sation filter can probably be realized with an RC network. Several continuous polynomial filters were considered for compensation of the clamped sampler. None of their amplitude-phase characteristics showed particular promise.

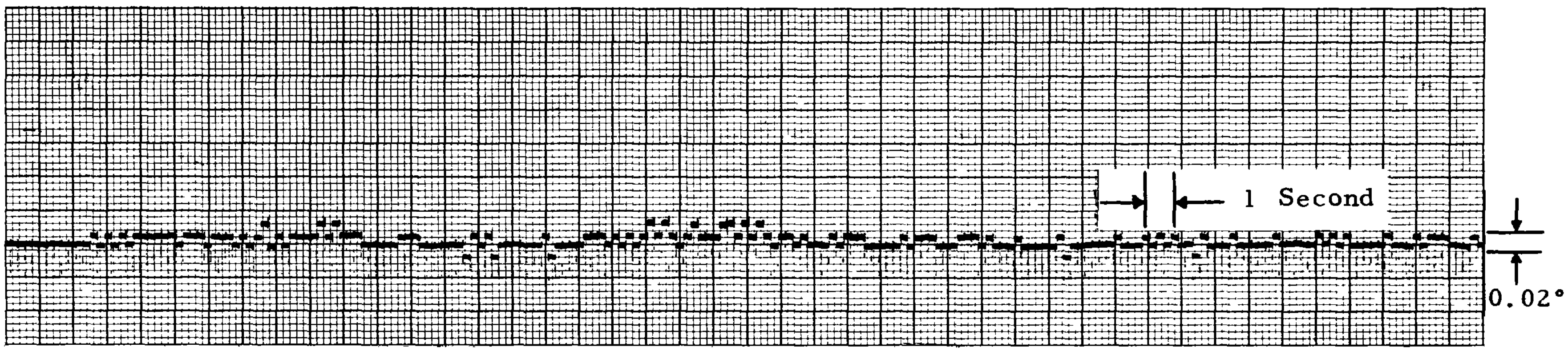
A sampled-data polynomial extrapolating filter, which will follow a first degree polynomial with zero error, was derived from the AN/MSN-3 angle tracker by rescaling ω according to the ratio of the data rates of the two systems. Although the amplitude-phase characteristics were somewhat superior to those of the combined clamped sampler and continuous polynomial filter, further investigation was not justified at that time.

A comparison of the characteristics of the three filter configurations investigated, indicates that those shown in Figure 3 probably represent the best compromise. Although the compatibility and stability requirements are essentially met, there is a range of frequencies over which noise components are unduly accentuated.

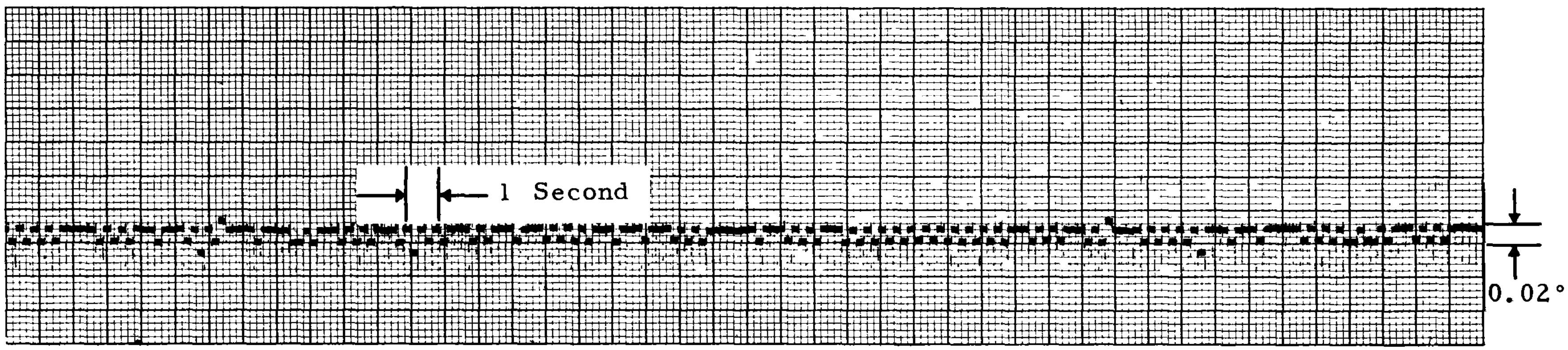
4. EXPECTED ERRORS IN ALTITUDE AND ALTITUDE RATE

Samples of Γ noise are shown in Figure 4. The essential difference in the noise of the Γ-2 run and the Γ-3 run is that the sample shown for the Γ-3 run has a much higher relative 15.7 rad/sec scan-noise component.

Functions F-1 and F-2 of run Γ-2 are shown in Figures 5 and 6. The strong scan noise component at 15.7 rad/sec is clearly evident. F-3 and F-4 of runs Γ-1 through Γ-4 are shown in Figures 7 and 8. These system accuracy characteristics constitute the essential results of this investigation. Their interpretation is based on approximating the closed-loop frequency



Recorded Data of Run Γ-3, Antenna Height = 16 Ft.



Recorded Data of Run Γ-2, Antenna Height = 8 Ft.

Figure 4. Samples of Γ Noise

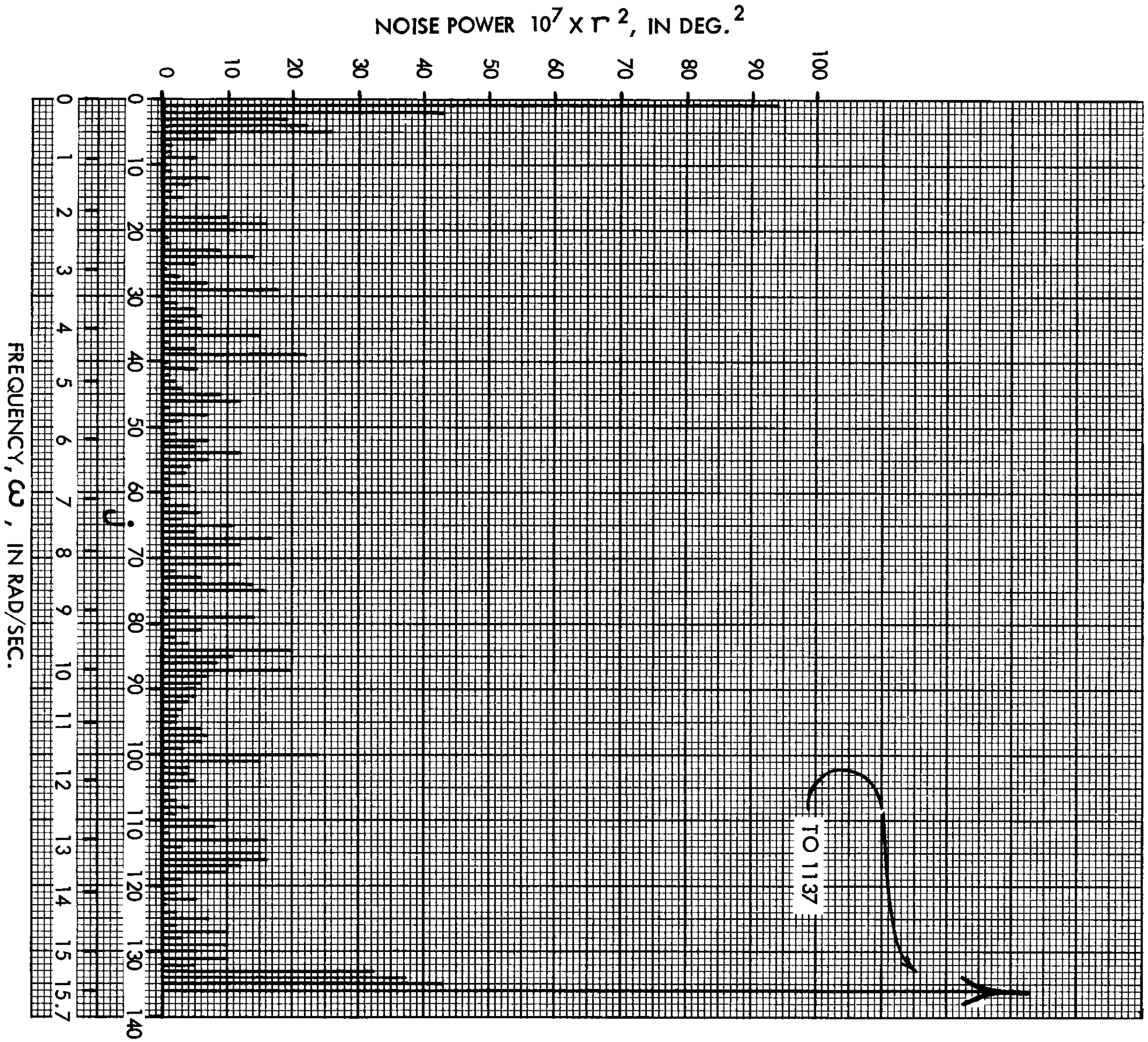
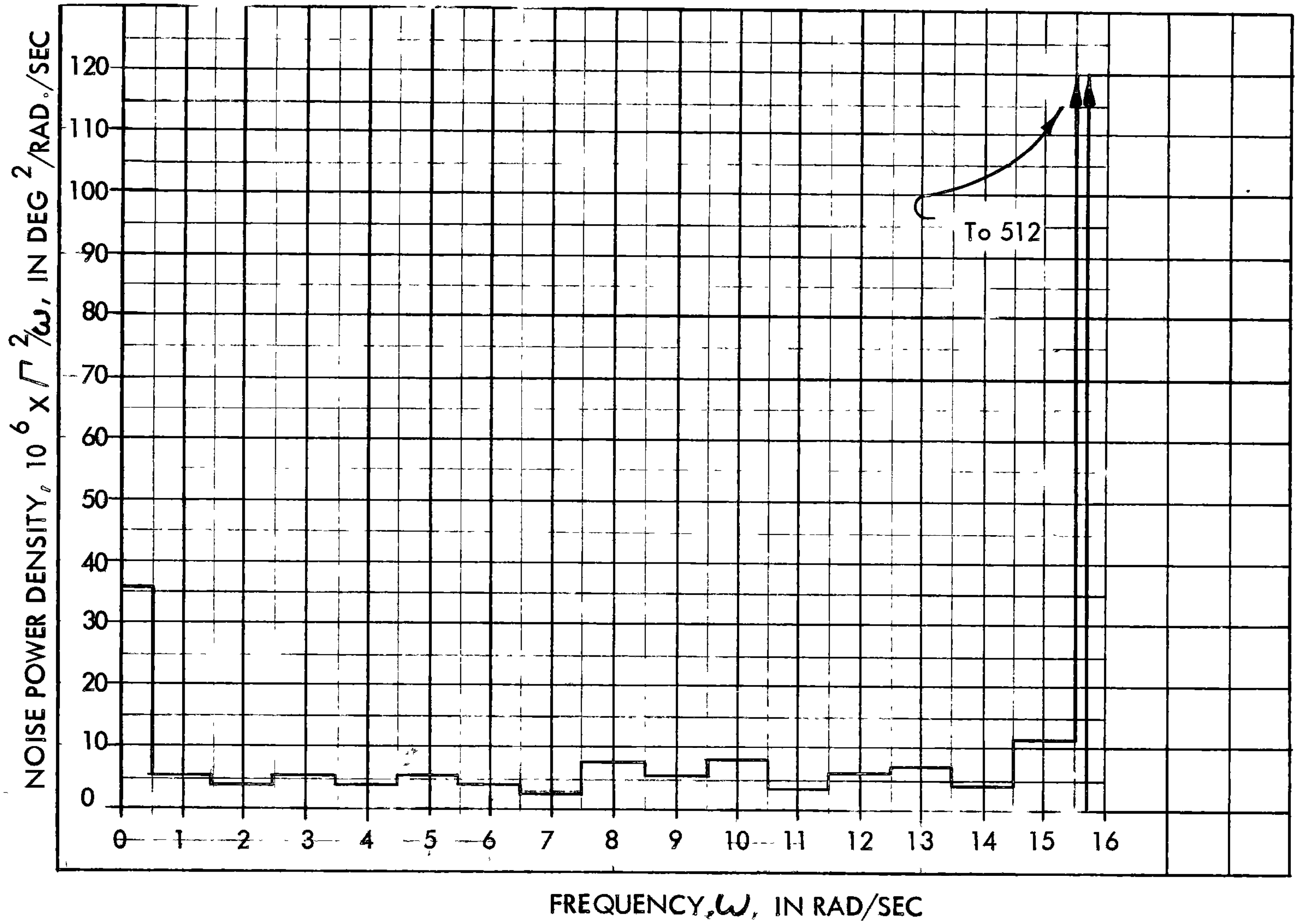


Figure 5. F-1 of Run Γ -2



F-2 OF RUN Γ -2

Figure 6.

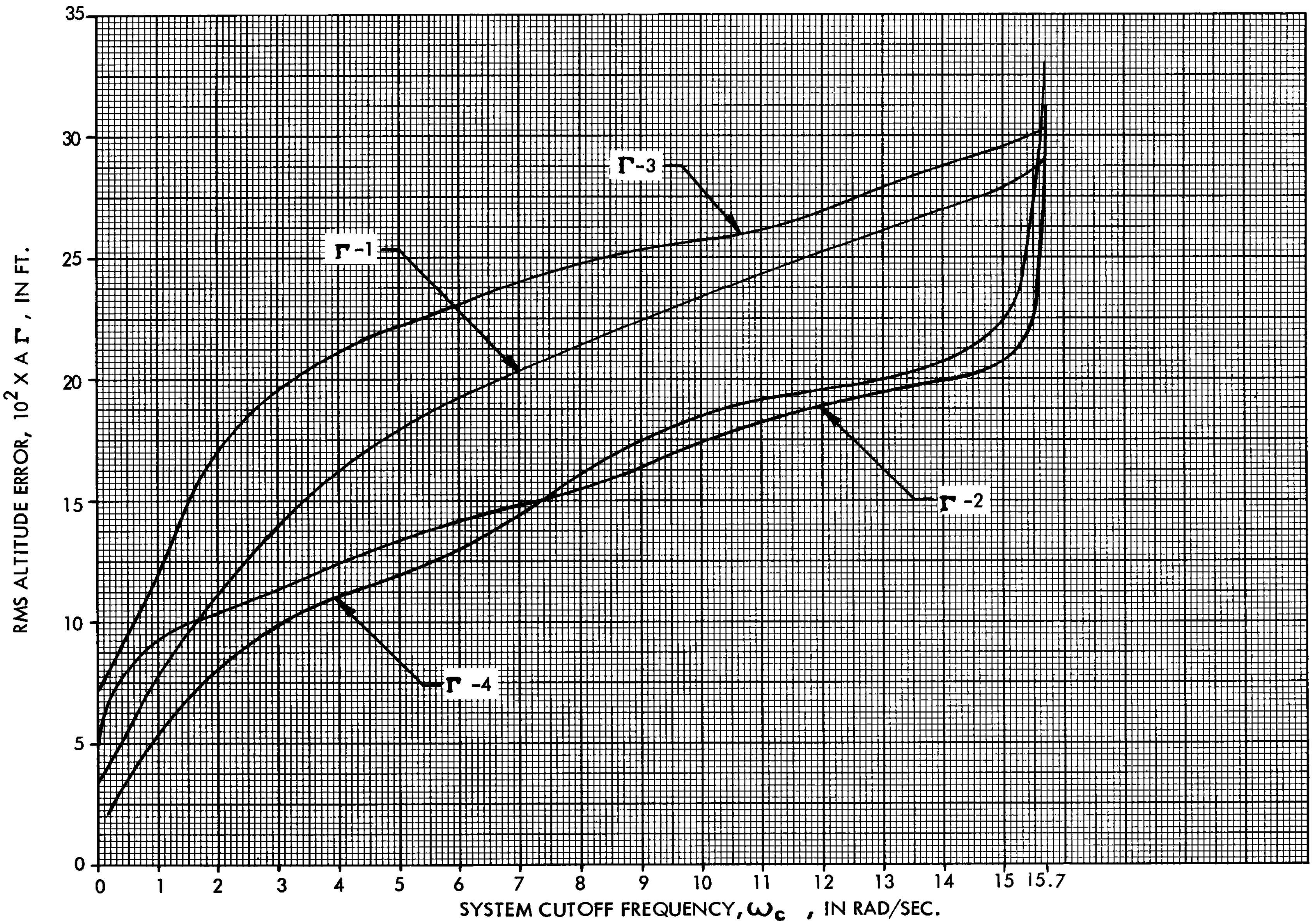


Figure 7. F-3 of Runs Γ-1 through Γ-4

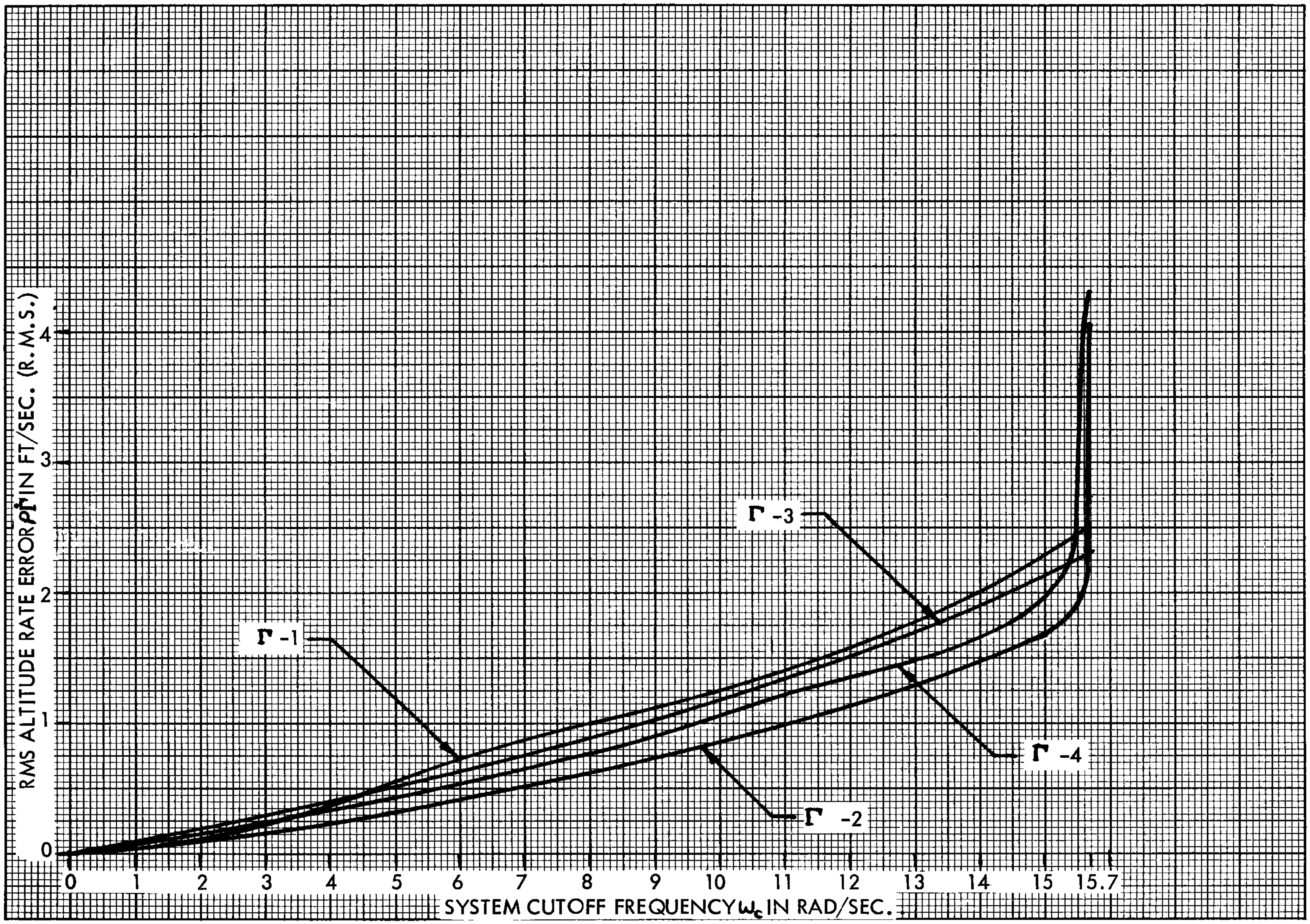


Figure 8. F-4 of Runs Γ-1 through Γ-4

response of the system under consideration by means of an ideal low-pass filter having a cutoff frequency of ω_c rad/sec. For example, consider a system having an equivalent cutoff frequency of 3 rad/sec. The curves show that at a range of 1200 feet the RMS error in altitude would be between 0.1 and 0.2 feet, and the RMS error in altitude rate would be between 0.15 and 0.35 feet/second. The distribution of these altitude errors should be well approximated by the Rayleigh distribution. On this basis, the probability that the RMS value will be exceeded is about 0.38, and the probability that twice the RMS value will be exceeded is about 0.02.

APPENDIX B

ERRORS IN REGAL COORDINATE CONVERTER EQUATIONS COMPARED TO SYSTEM TOLERANCES

The geometry and symbology* used in this investigation are illustrated in Figure 1. It will be noted that the difference in elevation between the transmitter position and the aiming point is assumed to be zero. In addition, interest is confined to the plane determined by y = L.

The equations that have been mechanized are of the form:

$$C_m = A - k$$

and

$$\Gamma m = \gamma \frac{A}{A-K}$$

where

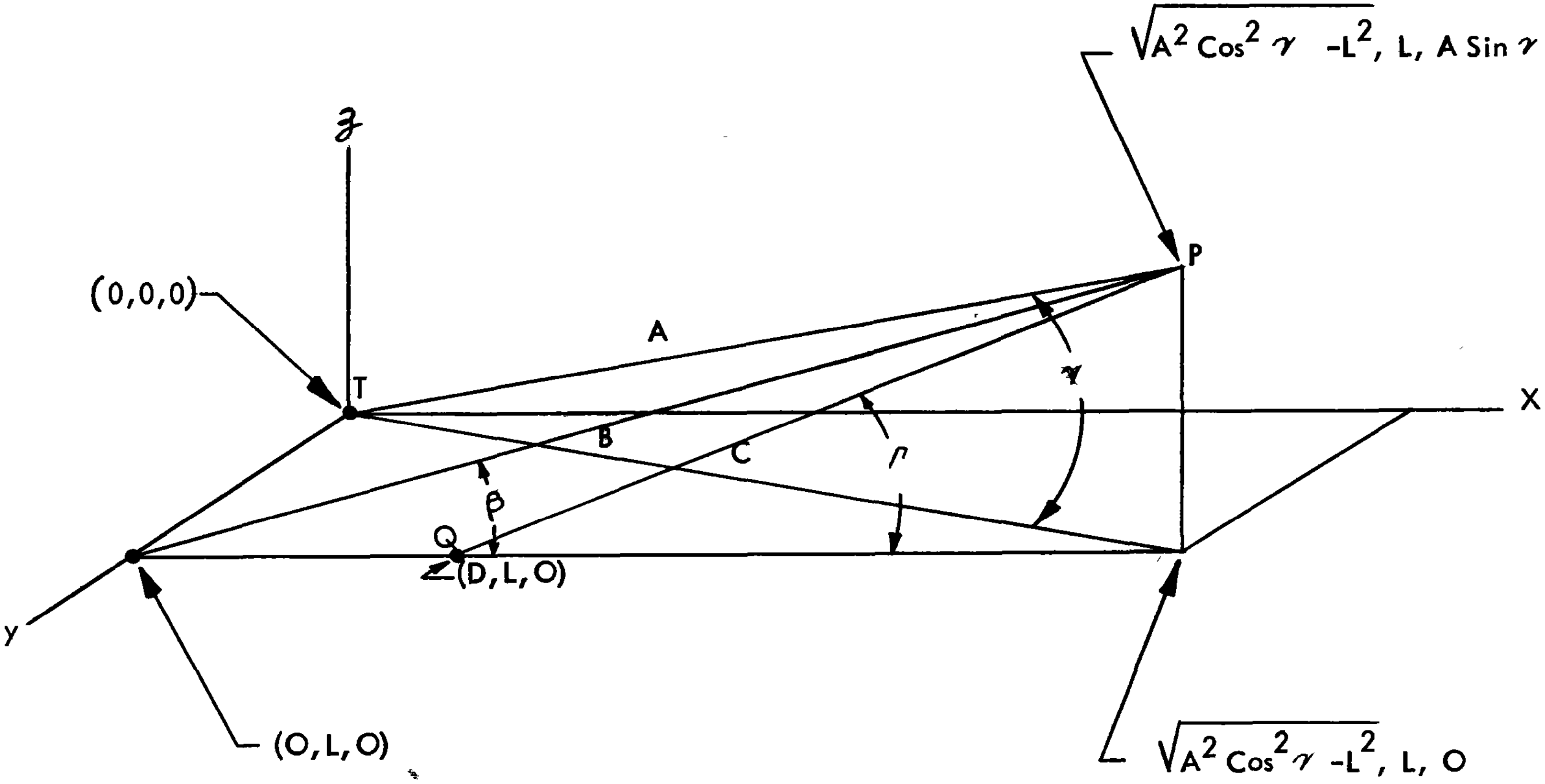
C_m = the computed value of C

Γ_m = the computed value of Γ

k = an adjustable constant

*In this appendix a departure has been made from the symbols used elsewhere in this report in order to avoid complicated subscripts. A table of comparative symbols for the basic parameters is as follows:

Symbol used in Appendix	Symbol used in Report
γ	Γ
A	ρ
Γ	Γ_x
C	ρ_x



T = Transmitter Position
P = Aircraft Position
Q = Aiming Point
L = Lateral Offset
D = Longitudinal Offset

Figure 1. Geometry of Coordinate Converter Problems

It has been shown that errors in Γ_m that increase rapidly with decreasing C can be avoided if $k = \sqrt{D^2 + L^2}$. On this basis the equations that have been investigated are:

$$C_m = A - \sqrt{D^2 + L^2}$$

$$\Gamma_m = \gamma \frac{A}{A - \sqrt{D^2 + L^2}}$$

If the computing error ΔC_m is defined as

$$\Delta C_m = C_m - C$$

and the computing error $\Delta\Gamma_m$ is defined as

$$\Delta \Gamma_m = \Gamma_m - \Gamma$$

It can be shown that:

$$\Delta C_m = \sqrt{L^2 + C^2 + D^2 + CD\cos\Gamma} - \sqrt{D^2 + L^2} - C$$

and

$$\Delta \Gamma_m = \left[\sin^{-1} \frac{C \sin \Gamma}{A}\right] \frac{A}{(A - \sqrt{D^2 + L^2})} - \Gamma$$

The above expressions yield the computational errors of the coordinate converter unit on the assumption that the input data from the REGAL receiver is perfect.

The errors in the coordinate converter outputs due to the errors in the basic REGAL data will now be considered.

It can be shown that:

$$A = \sqrt{L^2 + C^2 + 2CD\cos\Gamma}$$

and

$$\gamma = \sin^{-1} \frac{C \sin \Gamma}{A}$$

By defining $A_e = A + \Delta A$ as the measured range to the transmitter site and $\gamma_e = \gamma + \Delta\gamma$ as the measured angle with respect to the transmitter site the following error functions can be determined.

$$\Delta C_A = \sqrt{A_e^2 - L^2 + D^2 - 2D - \sqrt{A_e^2 \cos^2 \gamma - L^2 - C}}$$

$$\Delta \Gamma A = \tan^{-1} \frac{A_e \sin \gamma}{\sqrt{A_e^2 \cos^2 \gamma - L^2 - D}} - \Gamma$$

$$\Delta C_\gamma = \sqrt{A^2 - L^2 + D^2 - 2D\sqrt{A^2 \cos^2 \gamma_e - L^2}} - C$$

$$\Delta \Gamma = \tan^{-1} \frac{A \sin \gamma_e}{\sqrt{A^2 \cos^2 \gamma_e - L^2 - D}} - \Gamma$$

Where

ΔC_A = the error in C due to Δ A alone

$\Delta \Gamma A$ = the error in Γ due to ΔA alone

ΔC_γ = the error in C due to $\Delta\gamma$ alone

$\Delta \Gamma$ = the error in Γ due to Δ A alone

Because $\Delta C_A / \Delta A$, $\Delta \Gamma A / \Delta A$, $\Delta C_\gamma / \Delta\gamma$, and $\Delta\Gamma\gamma / \Delta\gamma$ are all essentially constant over the ranges of Δ A and $\Delta\gamma$ of interest, superposition holds, and it is sufficient to determine the errors for the maximum positive values of Δ A and $\Delta\gamma$ permitted by the system specification.

These valued are:

A = 50 ft. for $A \leq 5000$ ft

= 0.01A for $A > 5000$ ft

$\Delta\gamma$ = 0.05 Deg.

The envelopes of the system accuracy specification would thus be $|\Delta C_A| + |\Delta C_\gamma|$ referred to C and $|\Delta \Gamma_A| + |\Delta \Gamma_\gamma|$ referred to Γ.

These error envelopes and ΔC_m and $\Delta \Gamma_m$, which will be recalled to be the errors in the coordinate converter equations, have been determined for the combinations of Γ, D, and L that are of the most interest. The cases which represent practical boundaries for normal operating conditions are shown in Figures 2 and 3. For presentation purposes $|\Delta C_A| + |\Delta C_\gamma|$ and ΔC_m have been expressed as percentage errors in C and $|\Delta \Gamma_A| + |\Delta \Gamma_\gamma|$ and $\Delta \Gamma_\eta$ have been expressed as altitude errors.

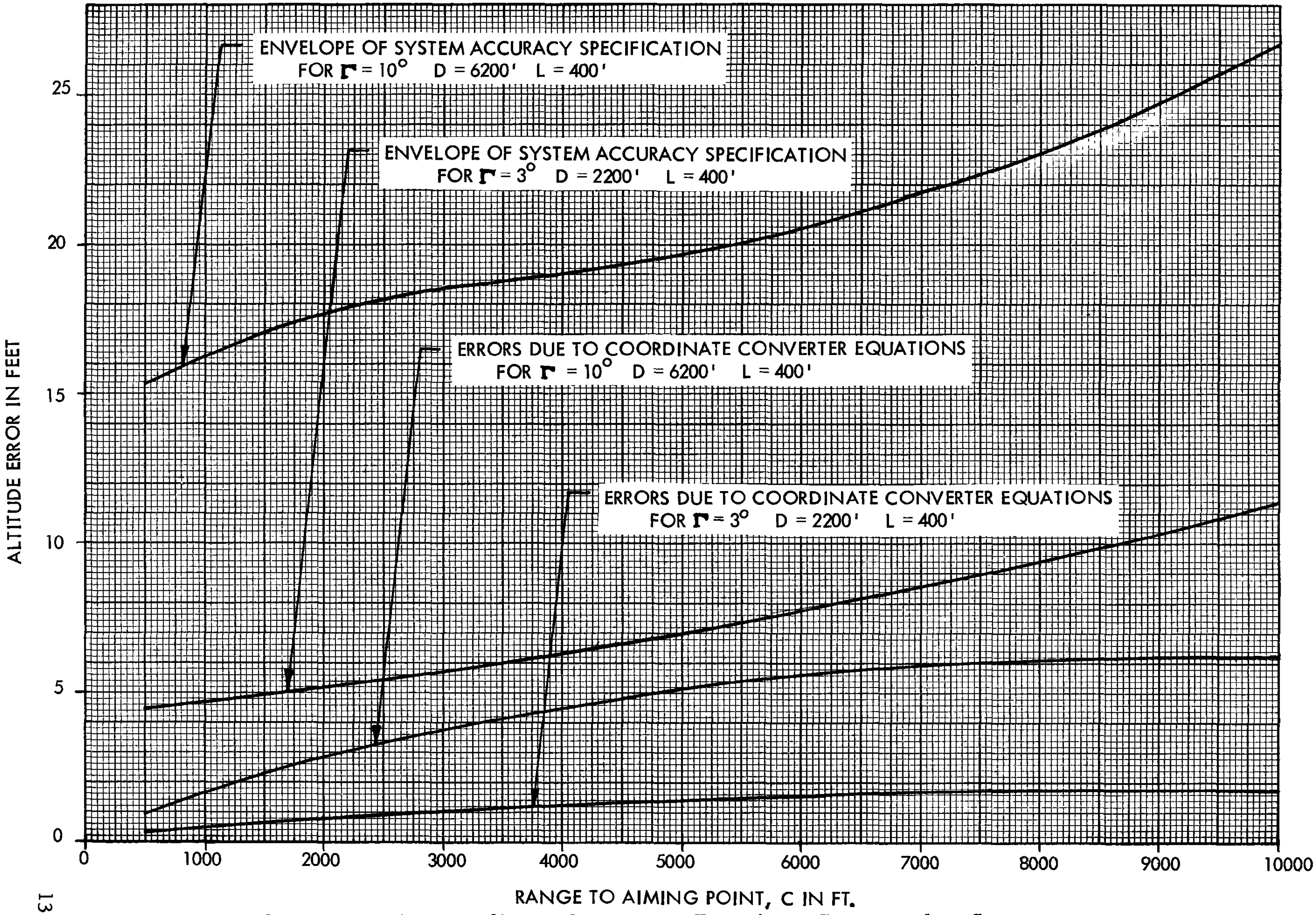


Figure 2. Errors in Coordinate Converter Equations Compared to System Tolerances for Altitude

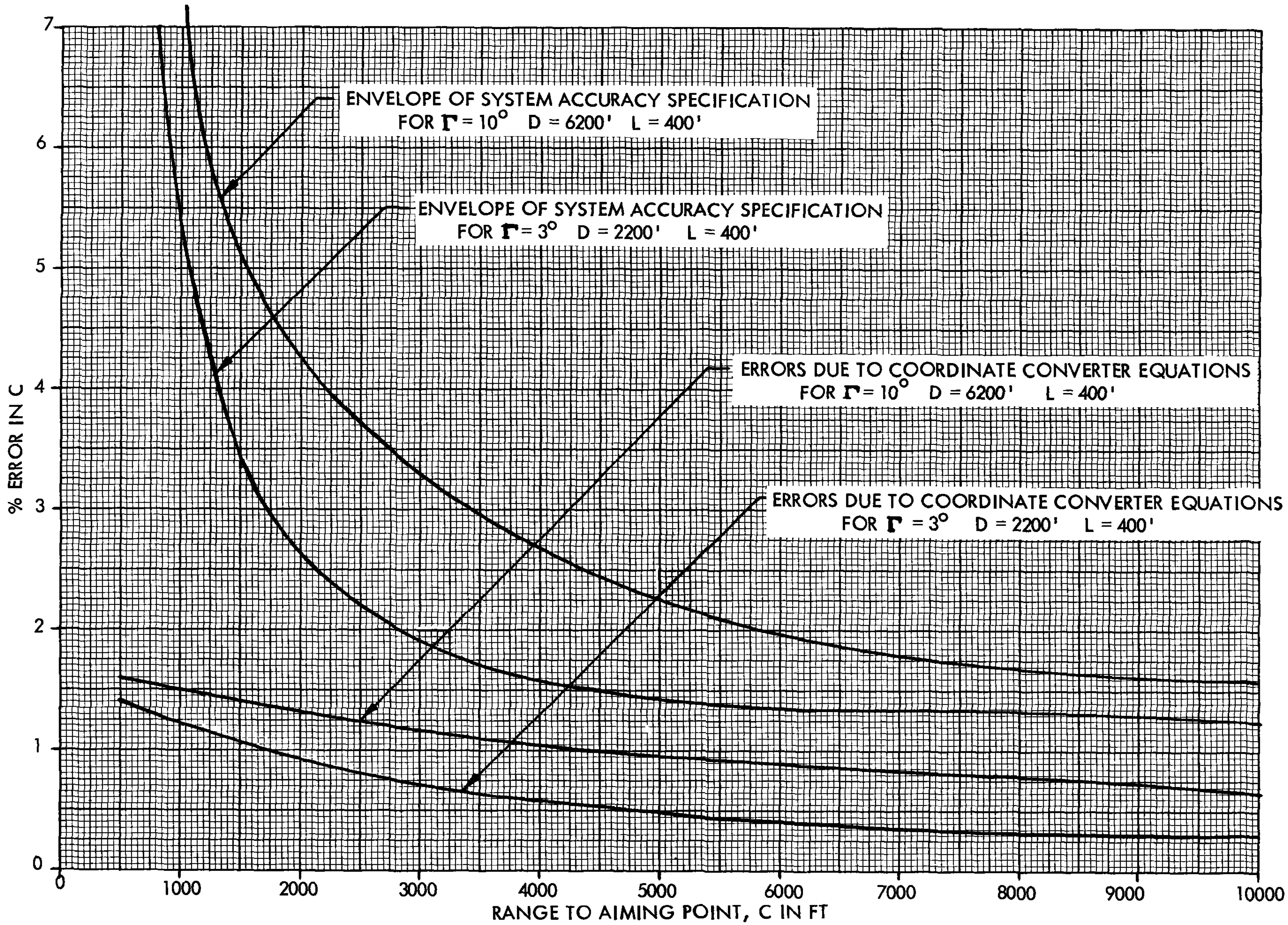


Figure 3. Errors in Coordinate Converter Equations Compared to System Tolerances for Altitude Rate