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A STUDY OF THE AIR TRAFFIC CONTROL RADAR BEACON SYSTEM CHARACTERISTICS

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by

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SUMMARY

This report presents the results of studies and tests made to define characteristics of the Air Traffic Control Radar Beacon System which are necessary for adequate system operation. All data presented is based on the premise that this system must be compatible with the military beacon system and discussions are limited to those characteristics that can be changed without affecting the feature of compatibility. Nominal operating frequencies, transmitted powers, pulse lengths, and pulse spacing are accepted as basic system requirements. This work was performed under Air Navigation Development Board Project 6.2.4

INTRODUCTION

The performance of the ATC radar beacon system depends on adequate signal levels in the interrogation and reply paths. For optimum performance at all participating sites, the effective radiated powers and receiver sensitivities of ground and airborne equipments must be held to close tolerances. Appreciable increase of interrogation power at one site may result in unsatisfactory results at nearby facilities. Under conditions of heavy interrogation, service may be denied to one site when an adjacent facility radiates excessive power. Excessive interrogation power or high transponder receiver sensitivity increases interrogation by ground antenna side lobes and unnecessary fruit results. Conversely, inadequate interrogation power or low transponder sensitivity will result in unreliable performance at medium and long ranges.

The use of several types of ground interrogator antennas having different beamwidths and gains can either cause excessive or insufficient system gain unless compensations are made. The length and type of antenna transmission line can be selected to offset the higher antenna gains so that the effective radiated powers are held within limits. Narrow-beam antennas cannot be rotated too rapidly else the number of replies per scan may give marginal performance when defruiting equipment is used. When fast scanning is a necessary operational requirement, a smaller antenna with a wider beamwidth may be required to provide reliable performance at the expense of azimuth resolution.

The siting of the ground equipment is most important for satisfactory system performance. Reflections of energy from the ground and buildings produce well-defined vertical lobe structures and cause false targets. This factor must be considered carefully before any permanent installation is made.

The signal level variations due to the airborne antenna radiation pattern can be equal to, or greater than, those due to the vertical lobe structure. Wing shielding, which may occur during aircraft turns, causes complete loss of targets. The pattern directivity of the airborne antenna can cause intermittent performance at medium and long ranges.

Side-lobe interrogations by the ground antenna are very severe at short ranges. A carefully adjusted STC (sensitivity-time-control) applied to the ground receiver can be effective only if all the airborne transponders transmit replies of equal power. Weak replies result in unsatisfactory targets while transponders having transmitted power above limits can cause intolerable side-lobe clutter and confusion on the ATC display. The use of improved ground antennas with lower side-lobe power would permit relaxation of the tight control of system gain.

The ATC Radar Beacon System is an amplitude sensitive system. In such a system it is imperative that amplitude variations be held as close to zero tolerance as is practicable.

This report contains the results of tests and studies conducted on the ATC Radar Beacon System to date. Although all the major results of this work are contained in this report, some of the tests are covered in more detail in other reports.[1, 2]

TESTS AND CALCULATIONS

System Range and Sensitivity Considerations

The present ground interrogator, ANDB Type 2.3NS1, delivers a minimum peak output power of 1000 watts at the antenna jack. If the conditions listed in Table I are assumed to represent an average installation, a transponder interrogation sensitivity of -70.6 dbm is required for interrogation at the range of 200 nautical miles under free-space propagation conditions.

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[1] David S. Crippen, Tirey K. Vickers, and Marvin H. Yost, "Initial Tests of the Secondary Radar System in Typical Terminal-Area Traffic Operations", Report No. 268, Technical Development Center, September 1956.

[2] Clair M. Anderson, David S. Crippen, Joseph E. Herrmann, Jr., and Francis M. McDermott, "Tests of the Traffic Capacity of the ANDB Radar Beacon System", Report No. 281 (Classified), Technical Development Center, December 1955.

TABLE I

INTERROGATION PATH GAINS AND LOSSES

Interrogator output power 1000 watts	60.0 dbm
Transmission line loss	-1.5 db
18-foot antenna gain	21.5 db
Antenna filter loss	-0.5 db
Reduction of antenna gain to half-power points	-3.0 db
Space attenuation for 200 nautical miles at 1030 mcs.	-144.1 db
Signal level at 200 nautical miles	-67.6 dbm
Effective aircraft antenna gain	0.0 db
Aircraft transmission line loss	-3.0 db
Required transponder sensitivity	-70.6 dbm

The space attenuation is calculated from the formula:

$$a = 36.62 + 20 \log f + 20 \log d$$

Where: f = frequency in megacycles
d = distance in statute miles
a = attenuation in db

a = 144.1 db for 200 nautical miles at 1030 mcs.
a = 144.6 db for 200 nautical miles at 1090 mcs.

The specified peak output power of the ATC Transponder, ANDB Type III, is 500 watts at the antenna jack. Representative reply path gains and losses are listed in Table II.

TABLE II

REPLY PATH GAINS AND LOSSES

ATC Transponder output power 500 watts	57.0 dbm
Aircraft transmission line loss	-3.0 db
Effective aircraft antenna gain	0.0 db
Space attenuation for 200 nautical miles at 1090 mcs	-144.6 db
Signal level at 200 nautical miles	-90.6 dbm
18-foot antenna gain	21.5 db
Antenna filter loss	-0.5 db
Reduction of antenna gain to half-power points	-3.0 db
Transmission line loss	-1.5 db
Required IR receiver sensitivity	-74.1 dbm

From the calculations, the level of the signals at the interrogator unit will be -74.1 dbm when an aircraft range of 200 nautical miles and free-space propagation are assumed. The interrogator-receiver sensitivity must be such that the signal plus noise-to-noise ratio will be at least 4 to 1 when the signal level is -74.1 dbm since the Video Interconnection Unit, or decoder, requires the above signal conditions for satisfactory performance.

Azimuth Resolution:

The CAA Surveillance type radars operating in the ten-centimeter band have narrow antenna beamwidths. The characteristics of three different antennas are shown in Table III.

TABLE III

AIRPORT SURVEILLANCE RADAR ANTENNA CHARACTERISTICS

	ASR-1	ASR-2	ASR-3
Half-power Beamwidth	3.0°	2.2°	2.5°
RPM	26	25	25

The ATC radar beacon system operates on the wave length of approximately 29 cm, which is almost three times that of the surveillance radars. For antennas of equal size as the radar antennas, the beamwidth of a beacon antenna is approximately three times wider at the half-power points.

The primary radar transmits a narrow beam and receives a reflection of the same relative magnitude using the same antenna for both operations. The two-way operation of the antenna system results in an effective narrowing of the pattern upon reception of a reflection. Therefore, the width of the radar targets displayed are usually slightly wider than the half-power beamwidth of the antenna.

The beacon system, which does not operate on the reflection principal, has an effective beamwidth which is usually greater than the half-power beamwidth. The interrogation path gain must be adequate for operation when the aircraft range is 200 nautical miles. At shorter ranges there is a considerable amount of reserve interrogation path gain so that the effective antenna interrogation beamwidth is broadened. Tests conducted at the TDC show an effective beamwidth of 180 degrees when the aircraft range is ten nautical miles. Therefore, as the range is reduced from 200 nautical miles, the interrogation beamwidth increases from that at the three db points. Interrogation is possible at points of the radiation pattern which are 30 db down from the nose of the beam when the aircraft is ten nautical miles from the ground facility. The characteristics of two presently available beacon antennas are shown on the next page.

TABLE IV

BEACON ANTENNA CHARACTERISTICS

	9-foot antenna	18-foot antenna
Beamwidth, 3 db down	7.0 degrees	3.5 degrees
Beamwidth, 10 db down	14.0 degrees	6 0 degrees
Side lobe level	-26 db	-24 db

The control of target width and the display of side lobe responses is accomplished by controlling the gain of the interrogator receiver. Although the airborne equipment is interrogated (and replying) over a wide beam angle, usually greater than that at the half-power points of the antenna pattern, the replies can be attenuated by a reduction of receiver sensitivity. This is, in effect, a means of narrowing the pattern of the beacon antenna and rejecting replies to side-lobe interrogations. However, if this means is to be effective for all aircraft, the transponder-radiated power must be within close tolerances. The length of transmission lines and thus the attenuation at any ground or aircraft installation can modify the system gain. Imposing close tolerances on the equipment output power and sensitivity will be ineffective if wide variations exist between transmission line installations.

Characteristics of several coaxial cables are given in Table V.

TABLE V

TRANSMISSION LINE ATTENUATION

	Attenuation db/100 ft. at 1000 mcs.
1. Styroflex:	
3/8" diameter	3.9
1/2" diameter	2.8
3/4" diameter	1.8
2. Andrew Heliax 7/8" diameter	1.55
3. Phelps-Dodge Foamflex 1/2" diameter	4
4. RG-8/U	9
5. RG-17/U	4

The sensitivity of the interrogator receiver must be carefully controlled when aircraft are near the interrogator to prevent the display of side lobes and, at the same time, provide a degree of reserve gain to compensate for signal fading. The causes of signal fading will be discussed in later paragraphs. The 18-foot antenna side-lobe signal levels are 21 db less than those at the half-power points of the beam. Thus, if the maximum reserve gain exceeds 21 db, side-lobe responses will be displayed. The gain of the interrogator receiver can be set to provide a normal reserve gain of ten db. Signal variations from plus 11 db to minus ten db may occur before the display of side lobes or a signal fade will be noted. Normal replies under free-space propagation conditions will then be displayed over the beamwidth of the antenna ten db down from the half-power points. This condition is shown in Fig. 1 and a suitable STC curve is shown in Fig. 2. If better azimuth resolution is a requirement for traffic control then larger antennas are necessary. The physical size of a narrow-beam beacon antenna imposes mechanical rotation and supporting problems. If larger beacon antennas are to be attached to the present radar pedestals, it is quite probable that additional radar antenna and tower bracing will be necessary. Installation of dual rotary joints for each S-band radar antenna so equipped will be required. Separate towers for mounting beacon antenna pedestals are another alternative. This arrangement permits a larger degree of flexibility in siting and antenna height and may be a definite requirement at some locations. However, the physical separation of individual towers creates a display problem which can be solved by the use of time-shared sweep circuitry or dual gun cathode ray tubes.[1] If the displays are modified to include time-shared sweep circuitry or dual-gun tubes, the radar and beacon antennas may rotate at different speeds. This may prove to be of advantage from an operational standpoint.

Interference

The large reserve gain at short ranges results in excessive side-lobe interrogation of the transponders. Table VI shows the reserve gain at several ranges. The following conditions are assumed:

IR output power 1000 watts peak	60.0 dbm
Transmission line loss	-1.5 db
18-foot antenna gain	21.5 db
Reduction of gain to half-power points	-3.0 db
Antenna filter loss	-0.5 db
Aircraft antenna gain	0.0 db
Aircraft transmission line loss	-3.0 db
ATC transponder sensitivity	-74.0 dbm

[1] William E. Miller and Lawrence B. Ii, "PPI Presentation of Time-Shared Videos Having Synchronized or Unsynchronized Antenna Rotation Rates," Report No. 290, Technical Development Center, June 1957

TABLE VI

RESERVE INTERROGATION GAIN

Range Nautical Miles	Reserve Interrogation Gain-db
1	49.4
5	35.4
10	29.4
18.6 (side lobe range)	24.0 (side lobe level)
50	15 4
100	9.4
200	3.4

The side lobes of the 18-foot antenna are 24 db down from the nose of the beam. As can be seen from the reserve gain table, the side lobes will interrogate the transponder at ranges less than 18.6 nautical miles. This added interrogation results in the generation of interference to other facilities, and is referred to as fruit. Also, due to the effects of vertical interference pattern lobes which will be discussed in another paragraph, the side lobe interrogation range can exceed 30 miles. If a facility was only interested in aircraft within 50 miles, then a 12-db reduction of interrogator power output would be useful. Such a reduction in power will reduce the interrogation radius by a factor of four and the interrogation area by a factor of 16. The effective elimination of fruit in an area where several ground installations are operated can be accomplished only by the use of additional equipment referred to as a defruiter. This is a coincidence comparing device that depends on at least two successive synchronized replies for single-defruiting action or three successive synchronized replies for double-defruiting action. It is quite important that over-interrogation conditions be avoided to prevent loss of targets, especially when defruiting equipment is used. When the reserve interrogation gain is great enough to permit side lobe triggering, the transponder duty cycle increases rapidly and the operation of only a few ground interrogators will cause over-interrogation effects so that the airborne equipment will not reply to every interrogation. If one reply is lost, then no output is obtained from the defruiter until either two or three successive replies are successfully received.

Pulse Recurrence Frequency

The maximum ground interrogation rate of the system is limited by the maximum range of the equipment. For 200-nautical-mile operation, allowing ten per cent for indicator recovery time, the maximum prf is 365 pps. In order to synchronize the interrogator pulse repetition rate with the ASR-2 and ASR-3 radars, a countdown of four-to-one results in the prf of 300 pps. Table VII shows the number of hits per scan for various repetition rates and antenna rotation speeds.

TABLE VII

HITS PER SCAN

PRF	9-foot Antenna 15 rpm	9-foot Antenna 25 rpm	18-foot Antenna 15 rpm	18-foot Antenna 25 rpm
100	15.5	9.3	6.7	4
150	23.4	14	10	6
200	31	18.7	13.3	8
250	39	23.3	16.7	10
300	46.5	28	20	12
350	54.5	32.6	23.4	14
400	62.2	37.4	26.7	16

The formula for deriving the number of hits per scan is given by:

$$\text{Hits/scan} = \frac{\text{prf} \times \text{beamwidth}}{6 \times \text{rpm}}$$

The beamwidth is expressed as the width at ten db points in degrees.

Reflections

Signal reflections from the sides of buildings or from other objects near the ground facility are frequently seen on the PPI. The signals to and from the aircraft are reflected from nearby objects when the ground interrogator antenna is pointing at such objects. The signal strength over this reflected path is often sufficient to provide a false target which may appear equally as strong as the real target. Under some conditions, the false target is actually stronger. This can occur when the position of the aircraft is in a null of the vertical lobe structure as seen over the direct transmission path. However, when viewed over the reflected path the aircraft may be in a favorable antenna lobe and stronger signals result. Usually the buildings or objects which cause trouble are within a mile of the antenna. Careful consideration must be given to selection of an interrogator site to avoid this condition. The location of an existing ASR antenna may not be suitable for beacon operation due to this condition.

Vertical Lobing

The ATC beacon should provide strong reliable replies at all distances within the range of the system. Actually there are several deficiencies in the system which result in occasional fades and weak signals. One cause of serious fading is the energy which is reflected from the surface of the earth. This energy mixes with the direct signal and causes a pattern of interference to be set up in space. If the surface of the earth was a perfect reflector, the amplitude of the interference pattern would vary from twice the normal free-space signal to complete fade-out. Normally, the reflection is not that intense but does cause signal level variations of plus five db to minus 20 db when the reflecting surface is flat ground. A typical interference pattern in the vertical plane is shown in Fig. 3. The angles of the lobe maxima and nulls in the interference pattern are given by the formula:

$$\sin B = \frac{n\lambda}{4\left(h_1 - \frac{d_1^2}{2}\right)} - \frac{d_1}{4586}$$

Where: $n = 1, 3, 5,$ ---- for lobe maxima
$n = 0, 2, 4,$ ---- for nulls
λ = wavelength in feet
h_1 - antenna height above ground in feet
$d_1 = \frac{4h_1^2}{n\lambda}$ expressed in nautical miles

This formula is essentially correct for either horizontal or vertical polarization when the grazing angles are less than five degrees. Figure 4 shows the angles of the first three nulls for various antenna heights above ground. The phase of the reflected energy from the surface of the earth is reversed 180 degrees at all angles of incidence for horizontal polarization. However, in the case of vertical polarization, the phase shift gradually approaches zero as the angle of incidence is increased. This is shown in Fig. 5. The position of the lobe maxima and nulls in the interference pattern is likewise gradually reversed. With horizontal polarization the magnitude of the reflected energy is affected only slightly with changes in the angle of incidence and the resulting nulls are deep at all vertical angles. However, the magnitude of the reflected energy for vertically polarized waves is greatly affected by the angle of incidence. For small grazing angles the reflected energy is greatest and produces deep nulls. A curve of the magnitude of the reflection coefficient plotted against grazing angle is shown in Fig. 6. The use of vertical polarization, therefore, is a definite advantage if the effects of the interference pattern are to be minimized. Fig. 7 shows the calculated field strength relative to free space for an antenna 25 feet high over a smooth sea. The maximum depth of nulls in this case is -10.5 db. However, for similar conditions over smooth rich soil the nulls are considerably deeper. Figure 8 is the result of a test flight made over the Indianapolis airport, while the calculated interference pattern over smooth soil is shown in Fig. 9. Table VIII gives the values of lobe maxima and nulls for several reflection coefficients.

TABLE VIII

EFFECT OF REFLECTION COEFFICIENT
UPON SIGNAL LEVEL VARIATION

Reflection Coefficient	Depth of Nulls - db	Lobe Maximum -db	Maximum Signal Level Variation - db
1.0	Inf.	6.0	Inf.
0.9	-20	5.58	25.58
0.8	-13.98	5.1	19.08
0.7	-10.44	4.6	15.04
0.6	- 7.96	4.08	12.04
0.5	-6.02	3.52	9.54
0.4	-4.48	2.92	7.4
0.3	-3.1	2.28	5.38
0.2	-1.92	1.58	3.5
0.1	-0.9	0.82	1.72

The point of reflection on the surface of the earth has much to do with the resulting interference pattern. This point can be determined by:

$$d = \frac{h}{\sin \theta}$$

Where: h is the antenna height above ground
θ is the angle of incidence
d is the distance from the antenna to the point of reflection

Actually, the reflection takes place over an elliptical area surrounding this point as shown in Fig. 10. For low antenna heights the reflection area is close to the antenna while for higher antennas the reflection area may extend for several miles. Figure 11 shows the reflection point distance from the antenna for targets in the center of the first null and for different antenna heights above ground. As the reflection point moves away and the reflection area increases, the surface irregularities and earth's curvature tend to reduce the depth of the nulls. Improved performance due to a less sharply defined interference pattern should be expected with a high antenna unless the surface remains level over most of the reflection area. If a low antenna is used at airports the smooth surface of the airports will produce well defined and severe nulls. The question of whether a surface is smooth or rough can be determined by use of the Rayleigh criterion:

$$h \sin x < \frac{\lambda}{8}$$

for the surface to be smooth where x is the grazing angle of the signal expressed in degrees.

The results of this criterion at 1030 mcs are shown in Table IX.

TABLE IX

REQUIREMENTS FOR SMOOTH REFLECTING SURFACES

Grazing Angle Degrees	Maximum Height of Irregularities for a Smooth Surface
1	6.82 feet
2	3.42
3	2.28
4	1.71
5	1.36

A test flight was made to measure the effect of rough ground upon the interference pattern. The beacon antenna was mounted 25 feet above ground which placed the first null at 1.02 degrees. The rough-ground criterion for this grazing angle is 6.82 feet. The antenna was aimed over a group of steel and cement block buildings approximately 20 high so that the reflection surface was rough. The results of the test flight made over this surface are shown in Fig. 12 and it is evident that the vertical lobe structure is free from the deep interference nulls.

The variation from free-space signal level due to the interference pattern over smooth ground is frequently as great as 20 db. If the interrogator receiver sensitivity is adjusted to prevent side lobe break-through when the aircraft is in maxima, then there will be unpreventable fades due to the nulls. The use of antennas with lower side lobe levels would obviously improve this situation.

The first two vertical nulls in the pattern are the most severe and have an important effect on the performance of the system. The position of these nulls over smooth ground have been calculated for several altitudes and are shown in Figs. 13 through 16. A study of their effect upon system performance when transponder sensitivity and power output are varied has been made. The interrogation path and reply path have been examined separately and the results shown in tables X and XI.

TABLE X

Effect of First Two Antenna Nulls upon Interrogation Path Coverage to Line-of-Sight Range

Aircraft Altitude feet	Line of sight Distance n.m.	Transponder Sensitivity - dbm	Calculated Fade-out Time Within Line-of sight Distance %	Calculated Maximum Range n.m.	Duration of Fade in First Null n.m.
5,000	93 nau.miles	78	6.13	87	0 miles
		77	6.45	86.5	0
		76	7.31	86	0
		75	7.54	85.5	0
		74	8.38	85	0
		73	8.93	84.3	0.3
		72	10.2	83.8	0.5
		71	11.1	83	0.8
		70	12.28	82.3	1.2
10,000	129	78	6.2	122	0.5
		77	6.78	121	0.75
		76	7.75	120	1.0
		75	8.92	119	1.5
		74	9.88	118	1.75
		73	10.47	117.5	2.0
		72	11.22	117	2.5
		71	12	116.5	3.0
		70	13.2	115.5	3.5
20,000	180	78	6.11	171	2.0
		77	6.94	170.5	3.0
		76	7.5	170	3.5
		75	8.33	169	4.0
		74	9.44	168	5.0
		73	11.1	167	6.0
		72	12.5	166	7.0
		71	13.9	165	8.0
		70	16.1	163	9.0
30,000	219	78	6.85	209	5
		77	8.22	208	6
		76	9.6	206	6.5
		75	10.5	205	7
		74	12.3	203	8
		73	13.7	202	9
		72	15.5	201	11
		71	16.9	200	12
		70	18.9	198	14

18-foot antenna 25 feet above smooth rich soil. IR transmitter power 1000 watts.

TABLE XI

Effect of First Two Antenna Nulls Upon Reply Path Coverage to Line-of-Sight Range

Aircraft Altitude feet	Line of Sight Distance	Transponder Output Power	Calculated Fade-out Time Within Line-of-Sight Distance	Calculated Maximum Range	Duration of Fade in First Null
5,000	93 miles	500 watts	12%	84.5 miles	2.5 miles
		-1 db	13	84	3
		-2 db	14	83	3.5
		-3 db	16	82	4
		-4 db	19.5	81	4.5
		-5 db	20	80	5
		-6 db	22	79	5.5
10,000	129	500 watts	9.75%	121	3
		-1 db	11	119	4
		-2 db	12.75	118	5
		-3 db	14.75	117.5	5.5
		-4 db	16.5	117	6
		-5 db	18	116	6.5
		-6 db	19	115	7.5
20,000	180	500 watts	7.25%	172	4
		-1 db	8.5	171	5
		-2 db	9.5	170	6
		-3 db	11.5	169	7
		-4 db	13	168	8
		-5 db	15	167	9
		-6 db	17	166	10
30,000	219	500 watts	8%	211	5
		-1 db	9.5	210	6
		-2 db	10	209	7
		-3 db	11	208	8
		-4 db	13.5	207.5	9
		-5 db	14.5	207	10
		-6 db	16.5	206.5	11

18-foot antenna 25 feet above smooth rich soil. IR receiver maximum sensitivity -84 dbm.

The airborne antenna pattern is not as well defined as the ground pattern but is a complex system of variations. This is due to the many curved and discontinuous surfaces on the fuselage of the aircraft. Engine nacelles, wings, wheels, etc. all contribute many sources of reflection. A typical pattern of a belly stub antenna mounted on a DC-3 is shown in Fig. 17. The variations in signal level exceed 16 db. When this variation is combined with the ground antenna interference pattern a signal fluctuation of over 41 db is possible. This is a maximum increase of nine db and a decrease of -32 db from the calculated free-space level. Wing shielding of the belly antenna during turns also results in signal loss and target fade-out. Improvement of the airborne radiation pattern is possible by use of a combination nose and tail antenna system.[2] Although the installation is complicated by long transmission lines and additional mechanical difficulties, the resulting pattern is greatly improved and wing shielding is eliminated.

Second-Time-Around Targets

The signals from distant aircraft within line-of-sight can appear on the PPI at closer ranges if the pulse repetition rate is too high for the system reserve power. The STC circuit in the ground receiver will be very effective in removing the distant replies from the display if they are received within the first 20 miles of the sweep. However, in cases where the range of the second-time-around target is greater than 20 miles, the STC has little effect on interrogator-receiver gain and a false target will be displayed. The curvature of the earth can be effectively used against this condition. If the prf of the interrogator is low enough, the replies of all aircraft within line of sight to one interrogation will be received before the next interrogation is transmitted and before the next display sweep is started. Figure 18 is plotted to show the relationship of range, altitude and pulse repetition frequency required to obtain or prevent second-time-around conditions.

Receiver Noise Figure

The minimum noise power in a receiver having a 15 mcs bandpass which is more than adequate is given by:

$$kTB$$

where: $k = 1.38 \times 10^{-23}$ joules/degree
$T = 291°K$
$B = 15 \times 10^{6}$ cycles/second

This noise power is equal to 6.03×10^{-14} watts.

[2]Federal Telecommunication Laboratories, Omnidirection Airplane Antenna Study, Department of the Navy Contract NOa(s)-12212

The signal power received from a transponder in an aircraft at 200 nautical miles can be calculated from the range formula:

$$R^2 = \frac{(\lambda)^2}{(4\pi)} \quad \frac{(Pt\ Gt\ Gr)}{Pr\ K}$$

Where: R = 200 nautical miles = 200 x 6080 feet
λ = 27.5 cm = 0.902 feet (1090 mcs)
Pt = 500 watts
Gt = Aircraft antenna gain equal to 1
Gr = 18-foot antenna gain equal to 141
K = Line loss and antenna gain correction equal to 6.3

Solving the above equation for Pr, the received power is 3.849×10^{-11} watts.

This is approximately 600 times the minimum noise power or a noise figure of 28.06 db. It is, therefore, well within the reach of practical receiver design to produce a suitable ground receiver having sufficient sensitivity under free-space propagation conditions. The sensitivity requirements for the interrogation path or transponder receiver similarly is well within practical design limits.

Frequency Tolerances

It is logical to impose close tolerance limitations on the ground equipment so that the airborne equipment may be simplified. For a given transponder receiver bandwidth the frequency stability requirements may be relaxed as the ground transmitter frequency stability is tightened. For interrogation of an airborne transponder, the required receiver RF bandpass can be determined by:

$$B = \frac{a}{T}$$

Where B = bandpass in mcs
a = 1.5
T = pulse duration in usec.

For interrogation pulses of 1 microsecond duration, the minimum bandpass is given by:

$$B = \frac{1.5}{1.0} = 1.5 \text{ mcs.}$$

Additional bandpass is necessary to allow for frequency drift in both the airborne receiver and the interrogator transmitter. For example, if the frequency stability of the ground transmitter was 1 mcs and the transponder receiver was held to ±2.5 mcs, the required rf bandpass would be 8.5 mcs.

The table in Fig. 19 lists various interrogation frequency tolerances of the ground and airborne equipments and their effect on the required transponder receiver bandpass.

A similar condition exists in the reply path. However, the ground receiver is required to reproduce the envelope of shorter pulses with high fidelity for maximum performance of the decoder equipment. The minimum video bandpass of the ground receiver is given by:

$$B = \frac{a}{T}$$

Where: B = video bandpass in mcs.
a = 0.35
T = pulse rise time in usec.
equal to 0.1

which is equal to 3.5 mcs for pulses with a rise time of 0.1 microsecond.

The rf bandpass of the ground receiver must be twice that of the video bandpass or 7 mcs. Additional bandpass must be added to this value to allow for the instability of the airborne transmitter and ground receiver. The table in Fig. 20 lists several reply frequency tolerances of the ground and airborne equipments and their associated effects.

Power and Sensitivity Tolerances

The interrogation path gain if allowed to vary over wide limits can either result in overinterrogation of nearby aircraft or the inability to interrogate distant transponders. A tight tolerance on the power output of the interrogator will minimize the sensitivity tolerance of the airborne units which is desirable from the airborne equipment maintenance standpoint. Figure 21 shows the effects upon interrogation range when the interrogator power output is varied. The side-lobe interrogation range is also presented for the same degree of power variation. If the interrogator power output was held to 1,000 watts with no variation, and the transponder receiver sensitivity was held to -74 dbm ±0 db, the effects of the vertical lobe structure could vary the interrogation path gain from -19 to 5 db or vary maximum interrogation range from 33 miles to 524 miles. The side-lobe interrogation range could also vary from 2.08 miles to 33 miles due to the lobing effect. The wide variation in interrogation field strength due to the lobe structure makes it impractical to transmit sufficient power for 100 per cent interrogation at 200 nautical miles. An increase of interrogator power over the 1,000 watt level or an increase of the beacon receiver sensitivity would also increase the side lobe interrogation range. This would be undesirable as the side lobes are capable of excessive interrogation range. Improved antennas with reduced side lobe energy would permit an increase in the interrogation path gain without increasing the side lobe interrogation. This would provide more reliable interrogation and should be considered if improved antennas become available.

The signal variations due to the aircraft antenna pattern are more unpredictable due to the constant motion of the aircraft. In general, they can be ignored in determining the signal level as they will seldom cause fades lasting for more than a few moments. (This is not true when the fade is due to wing shielding which may occur during turns.)

If both the ground interrogator power output and the airborne transponder sensitivity are permitted to change ±3 db in addition to the lobe variation, the interrogation range will vary from 16.5 miles to 1,048 miles. This is double the variation which was attributed to the vertical lobe structure alone.

It is apparent that signal fades will be unpreventable even with maximum control of the interrogator power and beacon sensitivity. The field strength variation due to the interference pattern can be much greater than the effect of most equipment tolerances. The location of the interrogator antenna can, therefore, be more important in some locations than the equipment parameters. The ideal location for an interrogator antenna would be free from all ground reflection. In practice this location would be either a hilltop, rough ground, or sea water in that preference order. Smooth ground such as found at airports should be avoided. There is some indication that the use of a counterpoise below the interrogator antenna may reduce the depths of the nulls at the lower elevation angles and the possibility of using counterpoises should be investigated.

Transponder Output Power

The transponder transmitter output power must be held to close limits so that interrogator STC provisions will be effective in preventing the display of replies to side lobes. The table in Fig. 22 shows the signal change required to cause side lobe breakthrough on the PPI or target fade-out for various power and sensitivity variations. The lobes in the antenna pattern may increase the field strength by a maximum of six db. If side lobe break-through is to be prevented, the six db increase should be allowed for in the "signal increase" column. For example, the 500-watt ±3 db power output and -84 dbm ±3db interrogator sensitivity conditions can cause side lobe breakthrough and should be rejected for use. The nulls in the vertical lobe structure can exceed 19 db and are so severe that target fading cannot be prevented. An improved ground antenna with lower side lobe energy would be one means of reducing signal fading since the improved antenna would permit a reduction of STC action and the use of greater reserve sensitivity in the ground receiver without increasing display of side lobe replies.

Figures 23 and 24 show calculated interrogation path signal levels when the reflecting surface is sea water and smooth soil.

Pulse Position

The common system ATC transponder replies with pulses that have a duration of 0.35 to 0.55 usec, a rise time of 0.1 usec or less, and a decay time of 0.2 usec or less. The number of transmitted pulses can change from two to nine pulses depending upon the reply code and are spaced in multiples of 2.9 usec. According to the code selected at the decoder control box, each 2.9 usec tap on the decoder delay line will either be connected to a coincidence circuit for decoding or to a killer circuit for the rejection of a false code. Codes with few information pulses are more susceptible to killing because more taps of the decoder delay line are connected to the killer circuits.

For decoding a proper code, the pulses contained in the pulse train must emerge from the delay line taps simultaneously. This coincidence of pulses produces an output indicating a proper code. The pulses transmitted by the transponder may vary somewhat in pulse spacing but in no case should the variation exceed the minimum required overlap for decoder operation. This minimum overlap of pulses is given by:

$$W_o = W - 2 \Delta t$$

Where: W_o = the pulse overlap required in usec

W = pulse width in usec

Δt = positional tolerance of complete system in usec

When considering flat top pulses with rise times of 0.1 usec and decay times of 0.2 usec, the minimum overlap for maximum decoder output is 0.19 usec as shown in Fig. 25. A decoder that operated in this manner would allow a system tolerance of ±0.08 usec for pulses of 0.35 usec duration. This tolerance may be considered as "system slack" and all pulses may vary this amount without additive effects. However, any variation above this value rapidly reduces decoder output and the root-mean-square method of summing tolerance may be used. If a decoder output which is 6 db less than maximum is considered as the minimum acceptable performance standard, then the required decoder overlap is reduced to 0 usec as shown in Fig. 26. A total system tolerance of ±0.175 is possible for 0.35 usec pulses but due to additive effects the individual pulse tolerances must be limited below this value. If all eight pulses are transmitted the individual pulse tolerance is ±0.12 usec as determined from the equations:

$$\Delta t_s = \sqrt{\Delta t_a^2 + \Delta t_g^2}$$

$$\text{and } \Delta t_a = \sqrt{7 \Delta t_p^2} \quad \text{for 8 pulse codes}$$

Where: Δt_s = total system tolerance

Δt_a = total airborne tolerance

Δt_g = total ground tolerance

Δt_p = pulse position tolerance

Δt_g (the ground equipment tolerance) is taken as being zero.

In consideration of future system expansion to a maximum code of 15 pulses the individual pulse tolerance would be:

$$\Delta t_a = \sqrt{14 \Delta t_p^2}$$

$$(0.175 - 0.080) = \sqrt{14 \Delta t_{p_1}^2}$$

where: $\Delta t_p = \Delta t_{p_1} + 0.08$

$$\Delta t_{p_1} = 0.0254$$

$$\Delta t_p = 0.0254 + 0.08 = \pm 0.11 \text{ usec}$$

These tolerances are based on ground equipments that have zero tolerance and are of interest only to show the theoretical limit of the system.

In considering the system as used with practical decoders there is both pulse shape distortion in the ground equipment and pulse position displacement introduced by the decoder. Tests made of the ANDB Type 2.3NS4a equipment show in Fig. 27 that the minimum required overlap is 0.25 usec for full output. A total system tolerance of ±0.05 usec for 0.35 usec pulses is allowable with no output reduction. If the decoder output reduced by 6 db from maximum is considered as the minimum acceptable performance standard, then the measured required decoder overlap is 0.03 usec. This allows a total system tolerance of ±0.16 usec. However, due to the summing of tolerances, all tolerances above ±0.05 usec must be determined by the root-mean-square method of summing. The total ground tolerance including all circuitry in the receiver, video amplifiers, remoting equipment, decoder, and delay line can be estimated at approximately ±0.1 usec. The total airborne equipment tolerance is then calculated as:

$$\Delta t_s = \sqrt{\Delta t_g^2 + \Delta t_a^2}$$

$$(0.16 - 0.05) = \sqrt{(0.10 - 0.05)^2 + \Delta t_{a_1}^2}$$

$$\Delta t_{a_1} = 0.098$$

$$\Delta t_a = 0.098 + 0.05 = 0.148 \text{ usec}$$

where Δt_s = total system

Δt_g = total ground tolerance

Δt_a = total airborne tolerance = $t_{a_1} + 0.05$

If all eight pulses are transmitted by the airborne transponder the individual pulse spacing tolerance is given by:

$$\Delta t_a = \sqrt{7 \Delta t_p^2}$$

$$(0.148 - 0.05) = \sqrt{7 \Delta t_{p_1}^2}$$

$$.0096 = 7 \Delta t_{p_1}^2$$

where Δt_p = individual pulse tolerance

$$= \Delta t_{p_1} + 0.05$$

$$\Delta t_{p_1}^2 = \frac{.0096}{7} = .00137$$

$$\Delta t_{p_1} = .037$$

$$\Delta t_p = .037 + .050 = \pm 0.087 \text{ usec}$$

Future system expansion to 15 pulse codes would require individual pulse spacing tolerance of

$$\Delta t_a = \sqrt{14 \Delta t_p^2}$$

$$(0.148 - 0.05) = \sqrt{14 \Delta t_{p_1}^2}$$

$$14 \Delta t_{p_1}^2 = .0096$$

$$\Delta t_{p_1} = \sqrt{.00069} = 0.0262$$

$$\Delta t_p = 0.026 + 0.050 = 0.076 \text{ usec}$$

A table in Fig. 28 shows the tolerances of pulses for various conditions. Data for a ground equipment tolerance of ±0.05 usec is also presented. Figure 29 presents the maximum pulse position tolerance allowable for 70 per cent decoder output.

Killing Effects

To prevent false code information on the PPI, the decoder equipment is designed to reject or kill output information when an extraneous pulse appears at an incorrect but properly spaced position. For maximum freedom from killing or garbling due to extraneous pulses, the decoder selectivity must be designed to fully utilize the pulse position accuracy of the transponder pulses. The selectivity of the killer taps on the decoder delay line depends upon the pulse duration and spacing tolerance. The length of the garble area is 2.8 nautical miles in range centered on each aircraft position. When aircraft transmit the caboose pulse for the identification of position function, the length will be increased an additional 0.7 nautical mile. The width of the garble area is equal to the effective beamwidth of the beacon antenna. The code selected at the decoder determines the number of killer taps that can cause killing of the output video. Code 00 connects all six taps to the killer circuit while Code 77 removes all taps from the killer circuit. Considering all codes, the average number of killer taps in 4.6. The width of the killer slot is equal to:

$$Wk = W + Ws$$

where: W = pulse duration in usec
Ws = killer tap selectivity in usec.

Figure 30 shows the killer circuit selectivity for several pulse widths. In order to reject false codes, the killer slot cannot be more selective than the decoding coincidence circuit. Table 31 shows the percentage of killed replies for different decoder selectivities.

Tests made on the present decoder show that the killer selectivity is 1.0 usec with 0.45 usec input pulses and a corresponding killing of 26.4 per cent of replies, average for all codes when the aircraft separation is such that garbling can occur.

The selectivity of the decoder coincidence circuit could be decreased by means of pulse stretching techniques to permit relaxation of the pulse position tolerances of the airborne equipment. However, the associated wide selectivity in the killer circuit would increase killing within the garble area. If maximum performance is desired of the decoder under reply garbling conditions, the selectivity of the decoder and the pulse tolerances must be kept to close limits.

System Tolerance

The maximum system pulse position tolerance is determined by the shortest pulse duration and the minimum required pulse overlap. With 0.35 usec pulses a minimum overlap of 0.078 usec is required allowing a maximum system tolerance of ±0.136 usec. An overlap of 0.078 usec gives a coincidence selectivity of 0.54 usec for 0.35 usec pulses.

The width of the killer slot is determined by the longest pulse duration and the selectivity of the decoder killer circuit. The killer circuit selectivity must be no sharper than the coincidence circuit selectivity which is 0.54 usec for 0.35 usec pulses. With 0.55 usec pulses the killer selectivity curve increases to 0.944 usec.

Present available decoders for the in-service tests are not perfect and do require an increase of pulse overlap for adequate output. Operation of the full 64 codes with this decoder requires a transponder pulse position accuracy within ±0.064 usec. If a perfect decoder were available, the airborne tolerance could be relaxed to ±0.1 usec. However, future plans for system code expansion will require airborne pulse position accuracy within ±0.095 usec even with a perfect decoder. Based on 70 per cent decoder output, satisfactory system operation can be expected during the service environment tests if the transponder pulse positions are held to ±0.06 usec. With improved ground equipment and additional pulse code assignment the future transponders should be held to ±0.08 usec.

RECOMMENDED CHARACTERISTICS

The following characteristics based on the previous discussion are recommended for compatible ATC beacon equipment:

A. Ground Interrogator

1. Transmitter Frequency: 1030 mcs ±0.2 mc.

2. Transmitter Power: 1000 to 2000 watts peak output measured at the antenna terminal across a 52-ohm resistive load at any prf from 50 to 410 pulses per second.

3. Transmitter Pulse Shape:

    a. Duration of 0.8 ±0.1 usec as measured at 50% of the peak amplitude.

    b. Rise time of 0.1 usec or less.

    c. Decay time of 0.2 usec or less.

    d. Amplitude of the two pulses shall be within 10% peak amplitude of each other.

    e. Pulse spacing shall be 8.0 ±0.1 usec.

4. Receiver Sensitivity: A tangential receiver sensitivity of not less than -90 dbm.

5. Receiver Frequency: 1090 mcs ±0.2 mcs.

6. Receiver RF Bandwidth: Not less than 9.5 mcs at 6 db points with present decoders. (13 mcs for improved decoders)

7. Video Response: Video output from receiver shall be a reproduction of the transponder pulses with rise and decay times not to exceed 0.1 usec and 0.2 usec, respectively.

The video shall be limited at 2.0 volts and sufficient gain shall be provided to produce at least 0.5 volt of average peak noise output when the GTC is disabled. A signal 21 db above a signal plus noise-to-noise ratio of 2 to 1 shall have no significant stretching.

8. GTC: The receiver gain shall be reduced at least 75 db below normal gain by a disabling gate which occurs before the transmitter is pulsed. At 15 usec, after the second pulse is transmitted, the receiver gain shall reach an adjustable value which is between 30 and 40 db below a sensitivity of -90 dbm. The gain shall continue to rise towards normal at the rate of 6 db each time the range is doubled. Maximum deviation from this gain vs time curve shall not exceed ±1.5 db at any point. The receiver shall be enabled for an adjustable period from 10 per cent to 80 per cent of the prf period.

9. Antenna Gain: Minimum gain shall be 21.5 db over an isotropic radiator for 200-mile operation.

10. Antenna Side Lobes: Down at least 24 db below the level of the main lobe.

11. Effective Radiated Power: 49.5 to 52.5 dbm for 200-mile operation. An ERP of 39 to 42 dbm is satisfactory for 30-mile terminal operation.

12. Transmission Line Loss: As required to meet effective radiated power requirements.

13. Antenna Scanning Speed: At least 10 hits per mode shall be received during each antenna scan.

14. Antenna Height: As required to minimize effects of vertical interference pattern, reflections and blind areas.

15. Polarization: Vertical polarization.

B. <u>ATC Airborne Transponder:</u>

1. Transmitter Frequency: 1090 mcs plus or minus 3.0 mcs.

2. Output Peak Power: 27 dbm ±3 db.

3. Reply Pulse Shape:

   a. Duration 0.35 to 0.55 usec.
   b. Rise time 0.1 usec or less.
   c. Decay time 0.2 usec or less.

4. Receiver Sensitivity: Normal -74 dbm ±3 db for 90% interrogation. Low -62 dbm ±3 db for 90% interrogation. For

interrogation rates from 1000 to 2000 per second the receiver sensitivity shall not be reduced more than 3 db. Above 2000 per second the receiver sensitivity shall be reduced by at least 20 db at 2500 per second.

5. Receiver Frequency: 1030 mcs ±3 mcs.

6. Receiver Bandwidth: 8.0 mcs at 6 db down.

7. Reply Characteristics: Each reply pulse train shall consist of two bracket pulses spaced 20.3 ±0.06 usec apart and up to 6 additional information pulses spaced each 2.9 ±0.06 usec from the first bracket pulse. A special identification caboose pulse shall be transmitted 4.35 ±0.1 usec from the second bracket pulse.

8. Interrogation Characteristics: Interrogation pulse pairs of 0.8 ±.1 usec duration spaced 8 usec ±0.1 usec shall interrogate the transponder. Circuitry shall be included to reject pulses which have a duration of less than 0.3 usec and more than 2.0 usec.

9. Reply Delay: Internal delay shall be 3.0 ±0.5 usec.

10. Range Jitter: Maximum range jitter on successive replies shall not exceed ±0.1 usec.

11. Effective radiated Power: 24 dbm ±3 db.

12. Transmission Line Loss: A nominal loss of 3 db sufficient to meet the ERP requirements.

13. Antenna: Essentially omni-directional in the horizontal plane. Vertical beamwidth at least ±30 degrees from the horizontal plane.

14. Polarization: Vertical polarization.

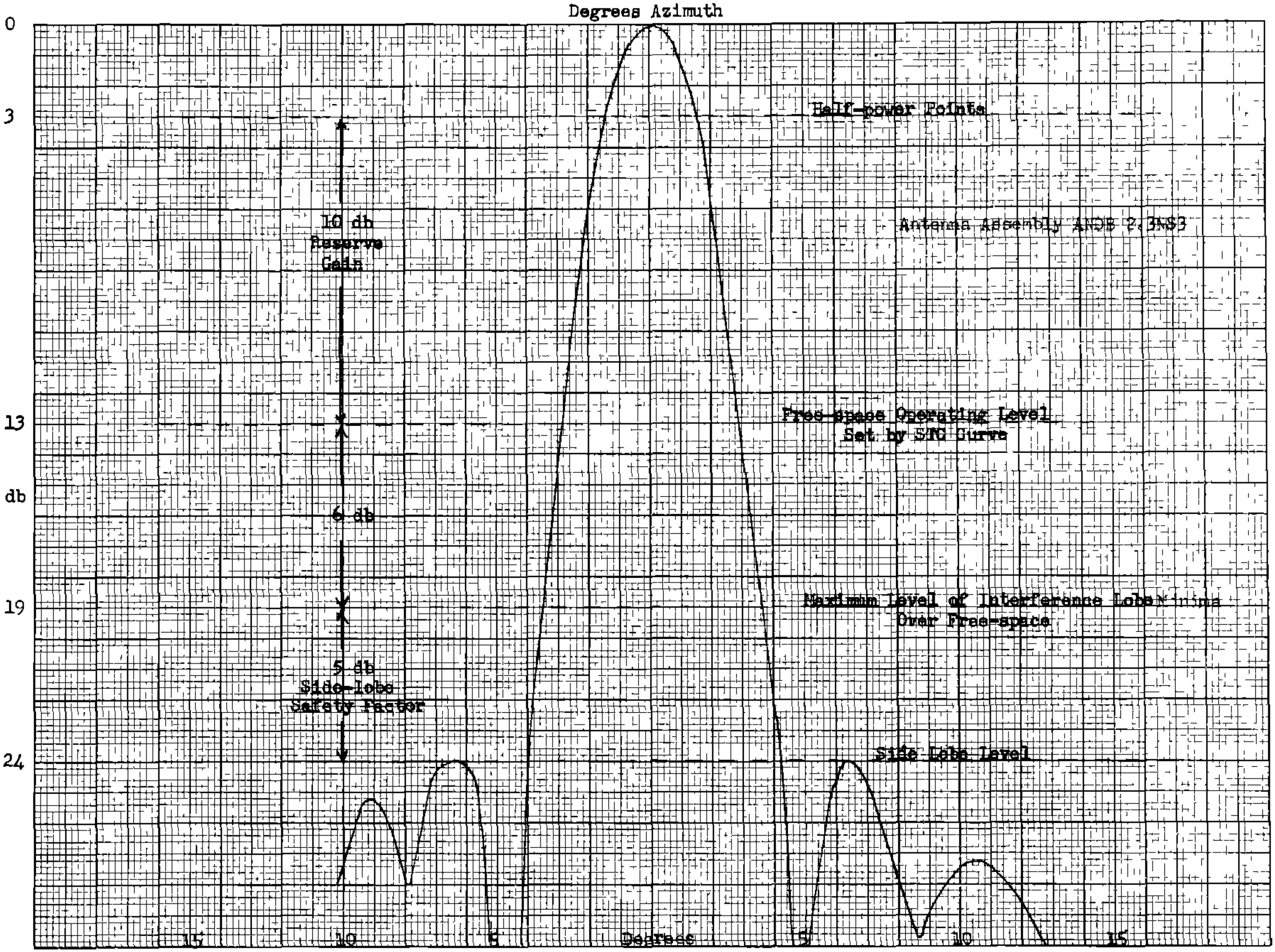
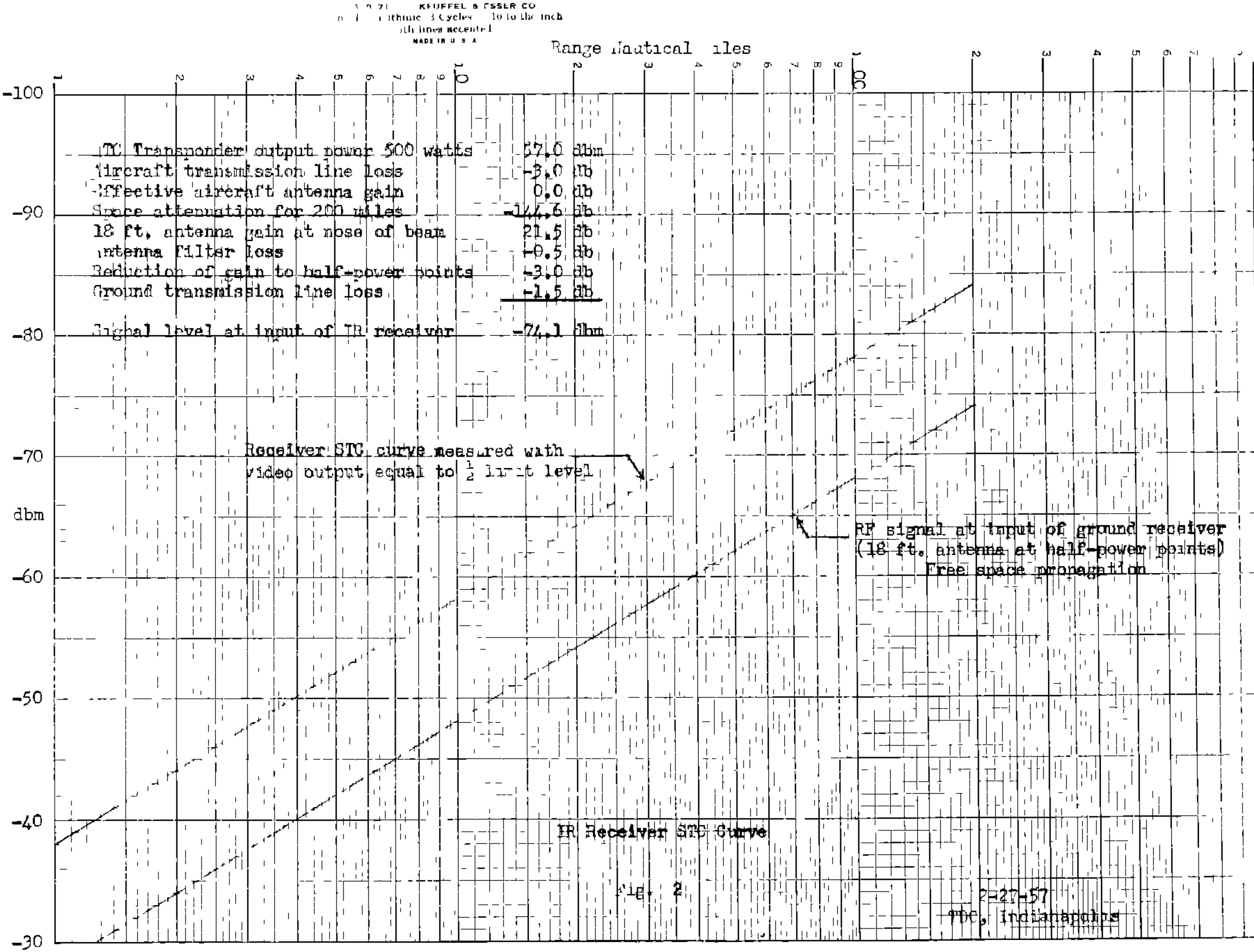


Fig. 1 Reply Path Signal Operating Point on Antenna Pattern


KEUFFEL & ESSER CO.
MADE IN U.S.A.
Range Nautical Miles
1
2
3
4
5
6
7
8
9
10
100
1000
-100
-90
-80
-70
-60
-50
-40
-30
dbm
ATC Transponder output power 500 watts 57.0 dbm
Aircraft transmission line loss -3.0 db
Effective aircraft antenna gain 0.0 db
Space attenuation for 200 miles -144.6 db
18 ft. antenna gain at nose of beam 21.5 db
Antenna filter loss -0.5 db
Reduction of gain to half-power points -3.0 db
Ground transmission line loss -1.5 db
Signal level at input of IR receiver -74.1 dbm
Receiver STC curve measured with video output equal to ½ limit level
RF signal at input of ground receiver
(18 ft. antenna at half-power points)
Free space propagation
IR Receiver STC Curve
Fig. 2
2-27-57
TDC, Indianapolis

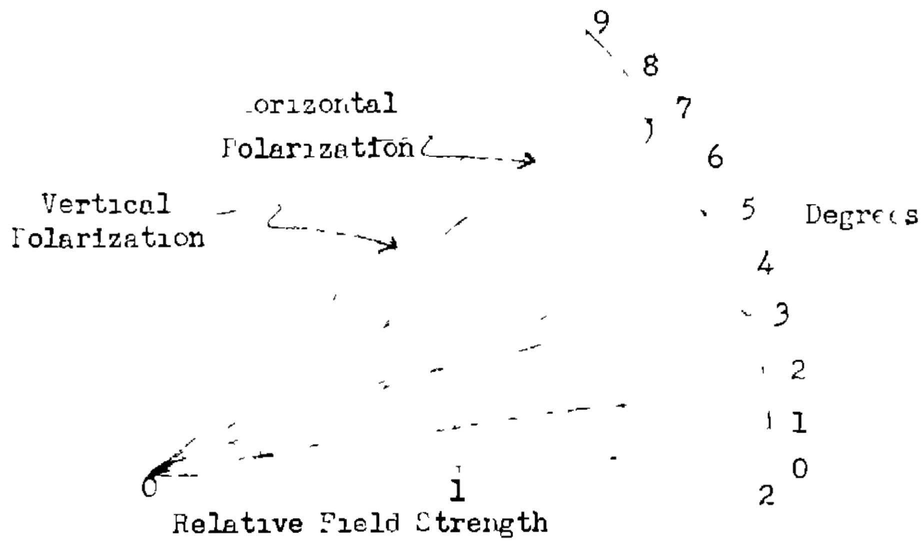


Fig. 3 Vertical lobe pattern resulting from reflections from earth. Antenna 13 ft. high. Frequency 1090 mcs.

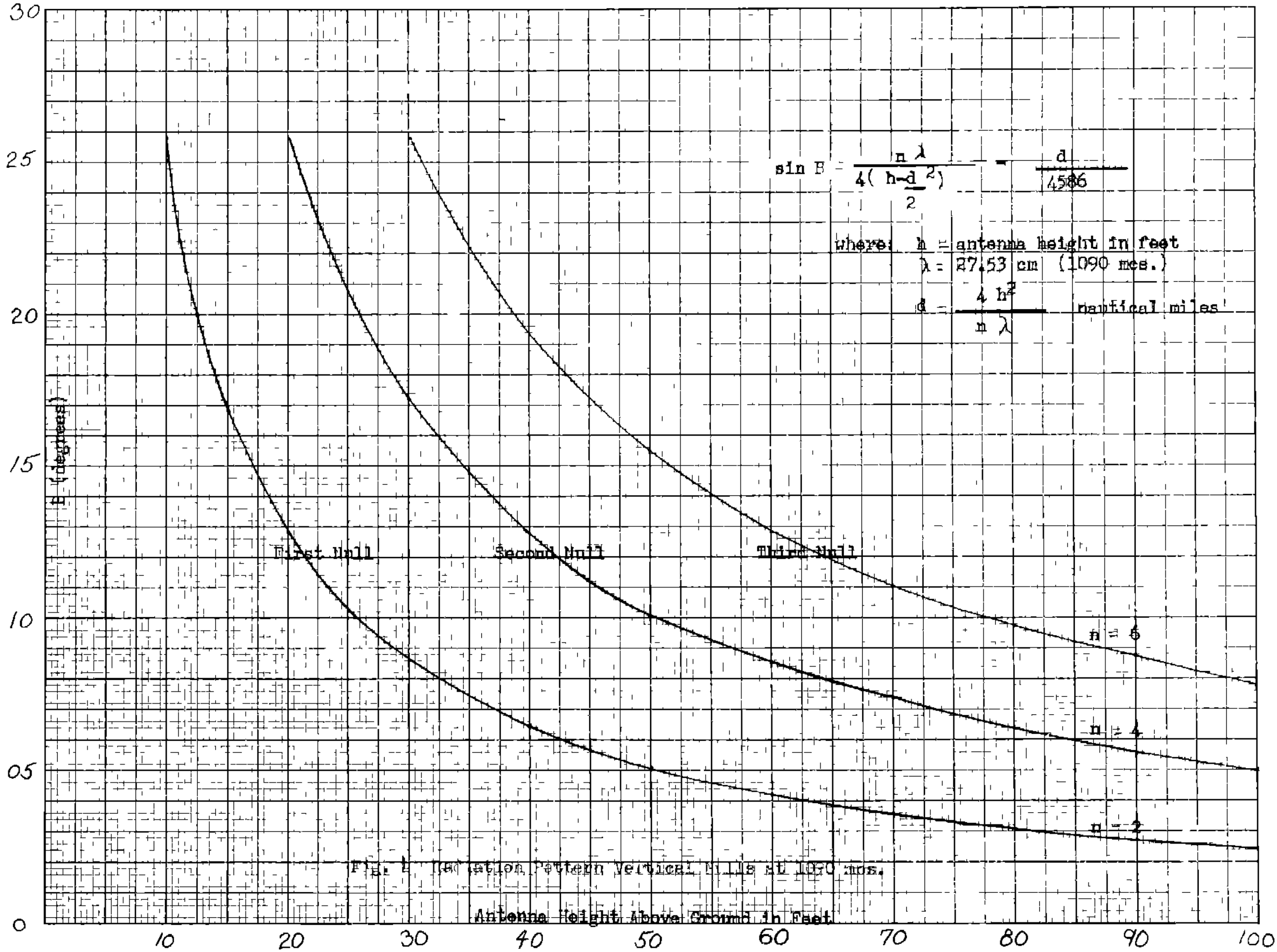
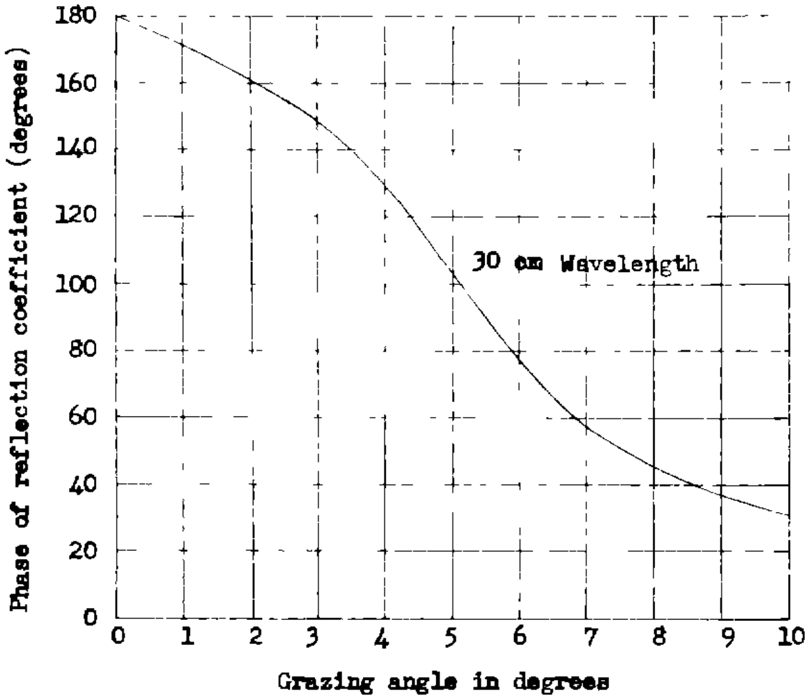


Fig. 1 Radiation Pattern Vertical Nulls at 1090 mcs.



Phase of the reflection coefficient as a function of grazing angle for a smooth sea and vertical polarization.

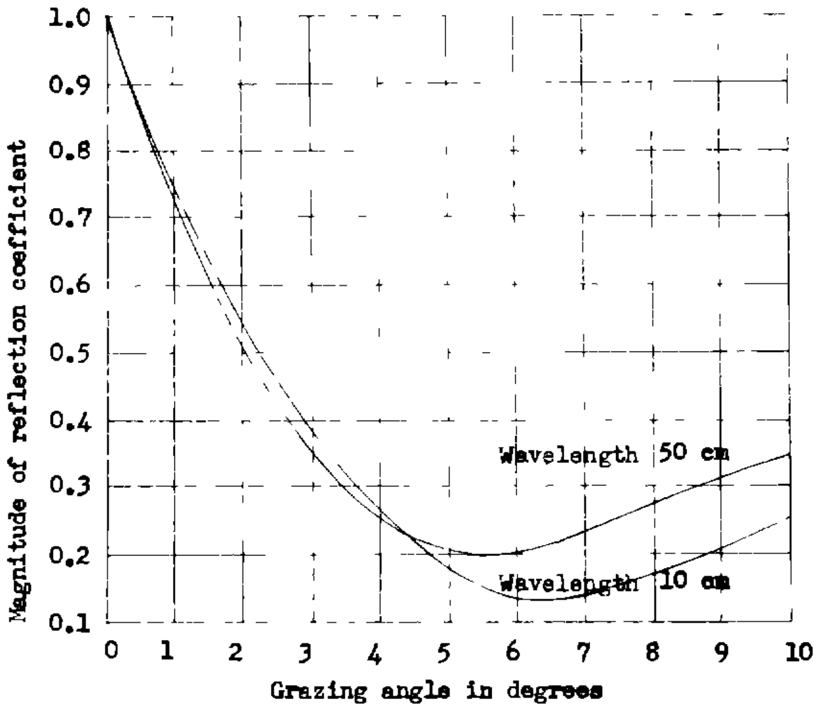


Fig. 5 **Magnitude of the reflection coefficient as a function of grazing angle for a smooth sea and vertical polarization.**

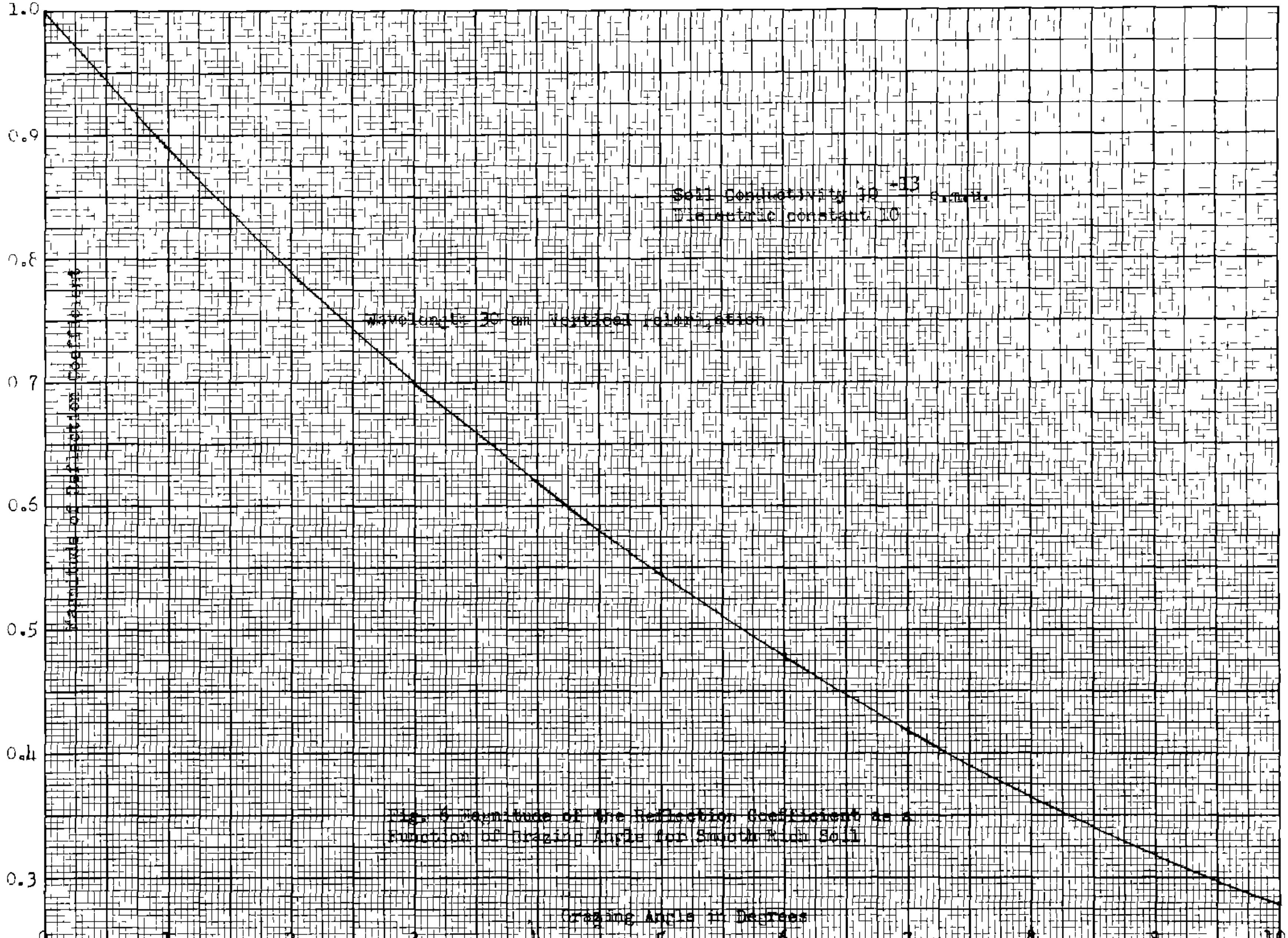


Fig. 6 Magnitude of the Reflection Coefficient as a Function of Grazing Angle for Smooth Rich Soil

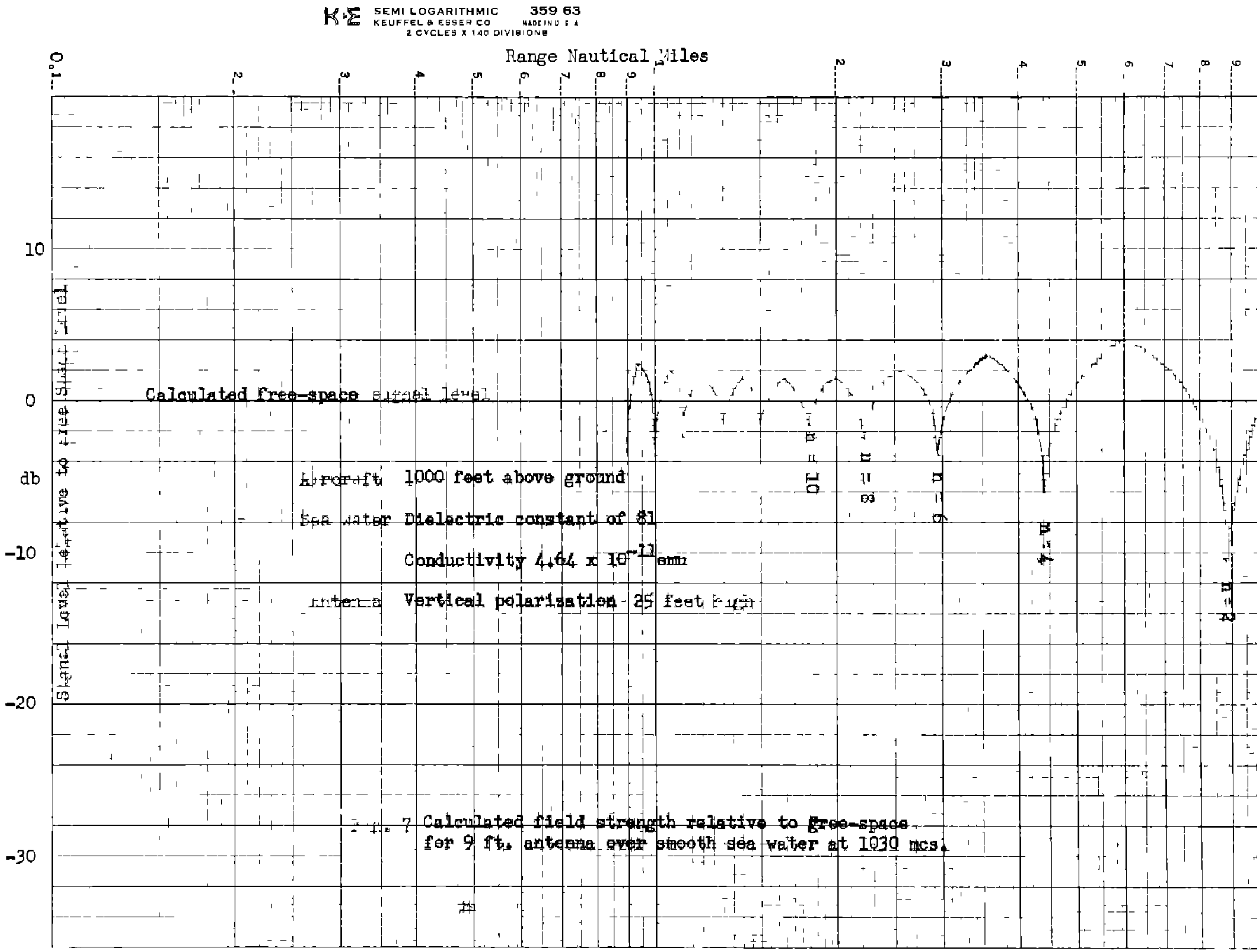
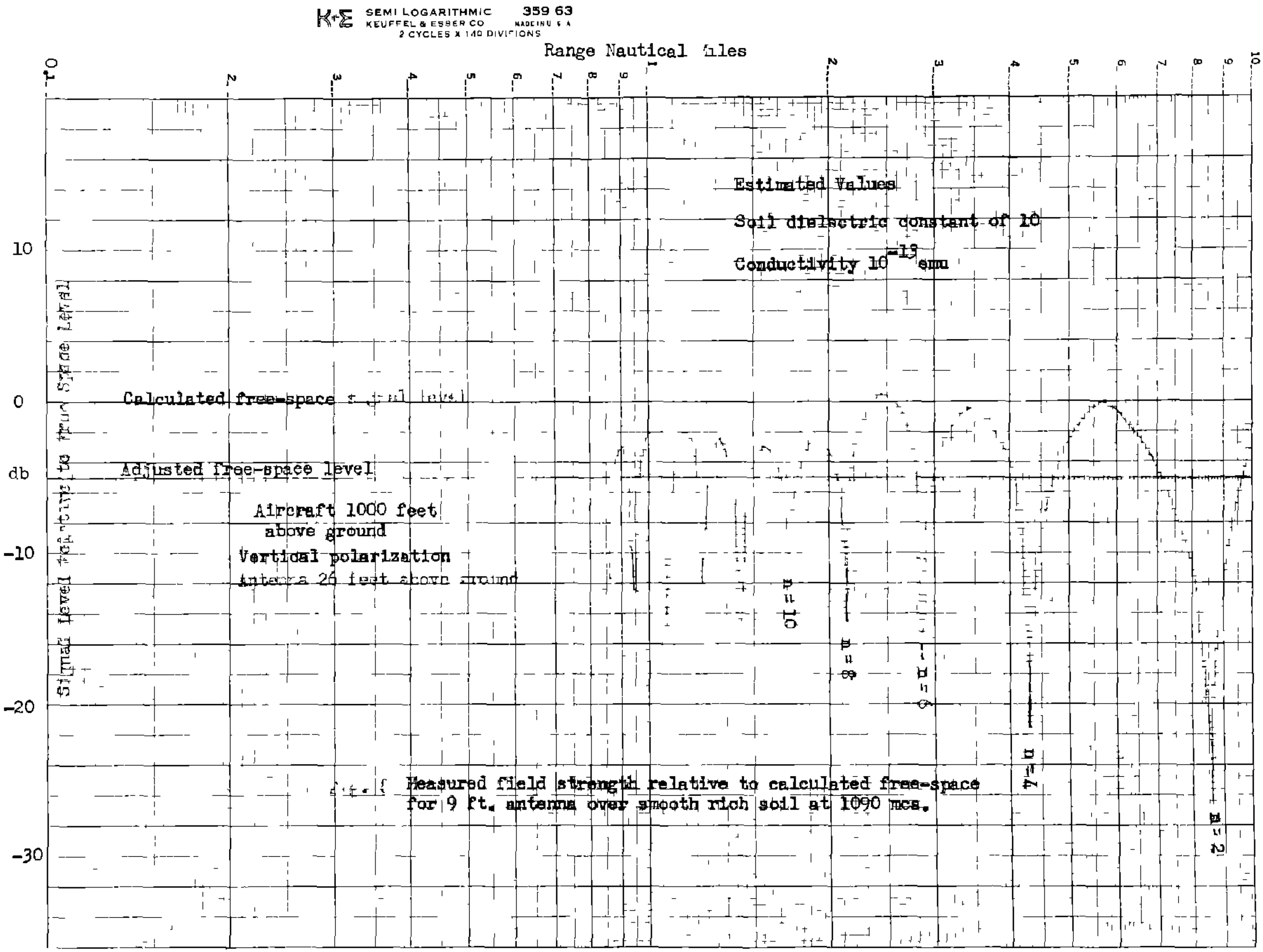


Fig. 7 Calculated field strength relative to free-space for 9 ft. antenna over smooth sea water at 1030 mcs.


K+E SEMI LOGARITHMIC 359 63
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 CYCLES X 140 DIVISIONS
Range Nautical Miles
Estimated Values
Soil dielectric constant of 10
Conductivity 10^-13 emu
Calculated free-space signal level
Adjusted free-space level
Aircraft 1000 feet above ground
Vertical polarization
Antenna 26 feet above ground
Signal level relative to free space level
db
n = 10
n = 8
n = 6
n = 4
n = 2
Measured field strength relative to calculated free-space for 9 ft. antenna over smooth rich soil at 1090 mcs.

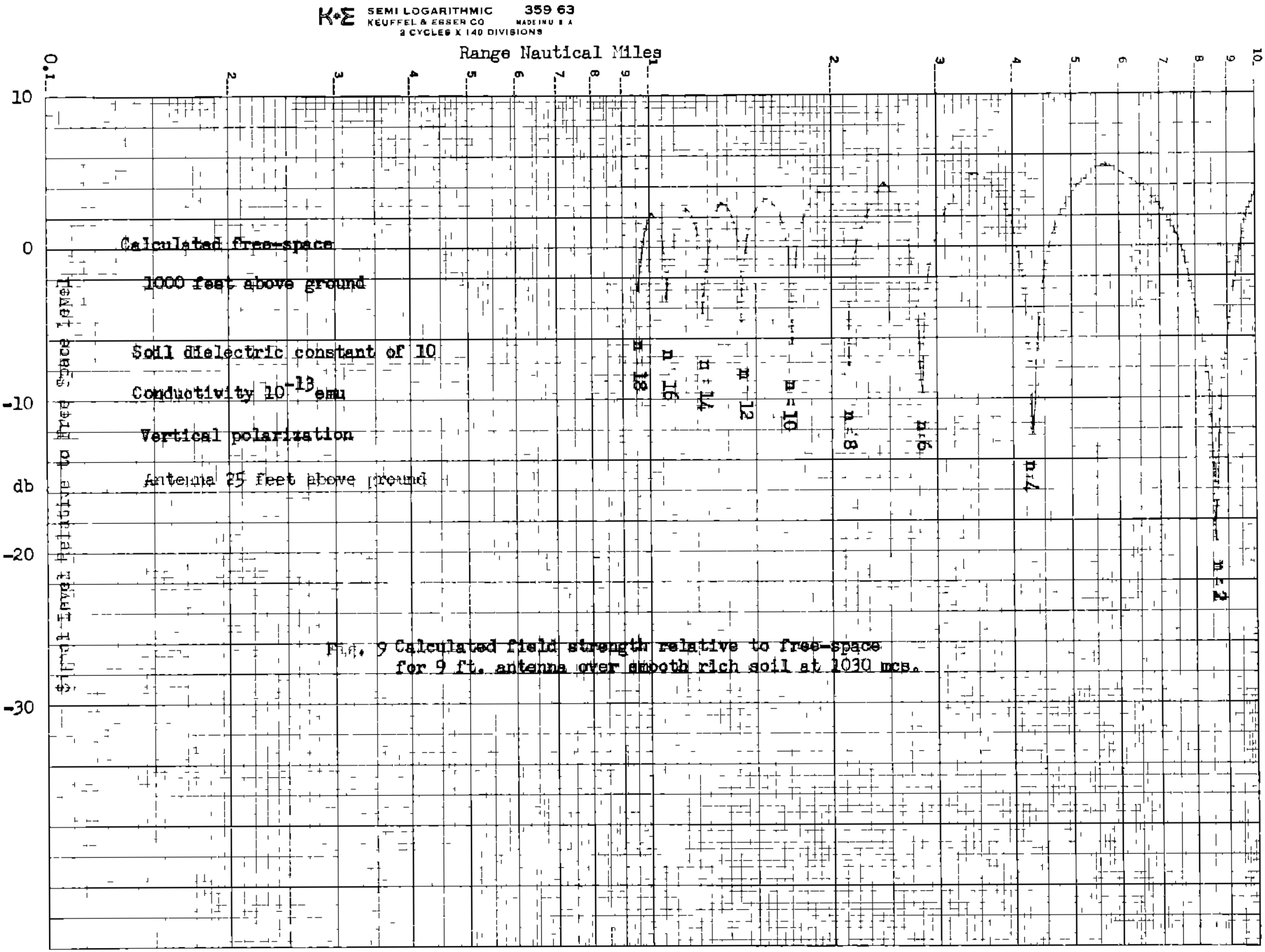


Fig. 9 Calculated field strength relative to free-space for 9 ft. antenna over smooth rich soil at 1030 mcs.

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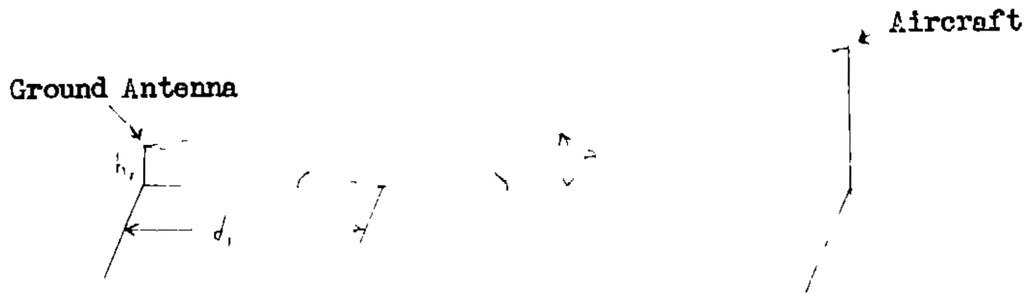


Fig.10 Elliptical reflection area shown over flat earth.

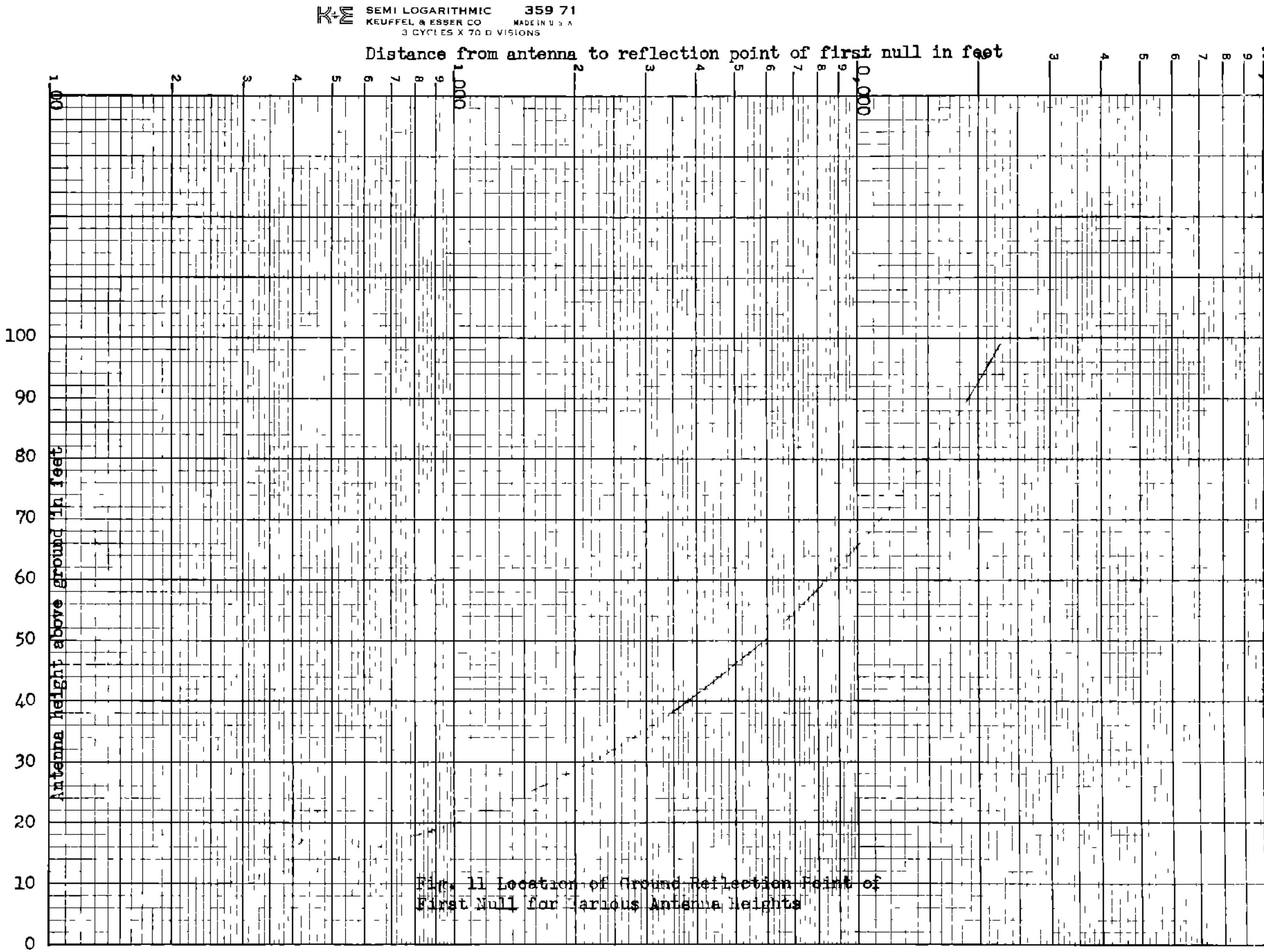


Fig. 11 Location of Ground Reflection Point of First Null for Various Antenna Heights

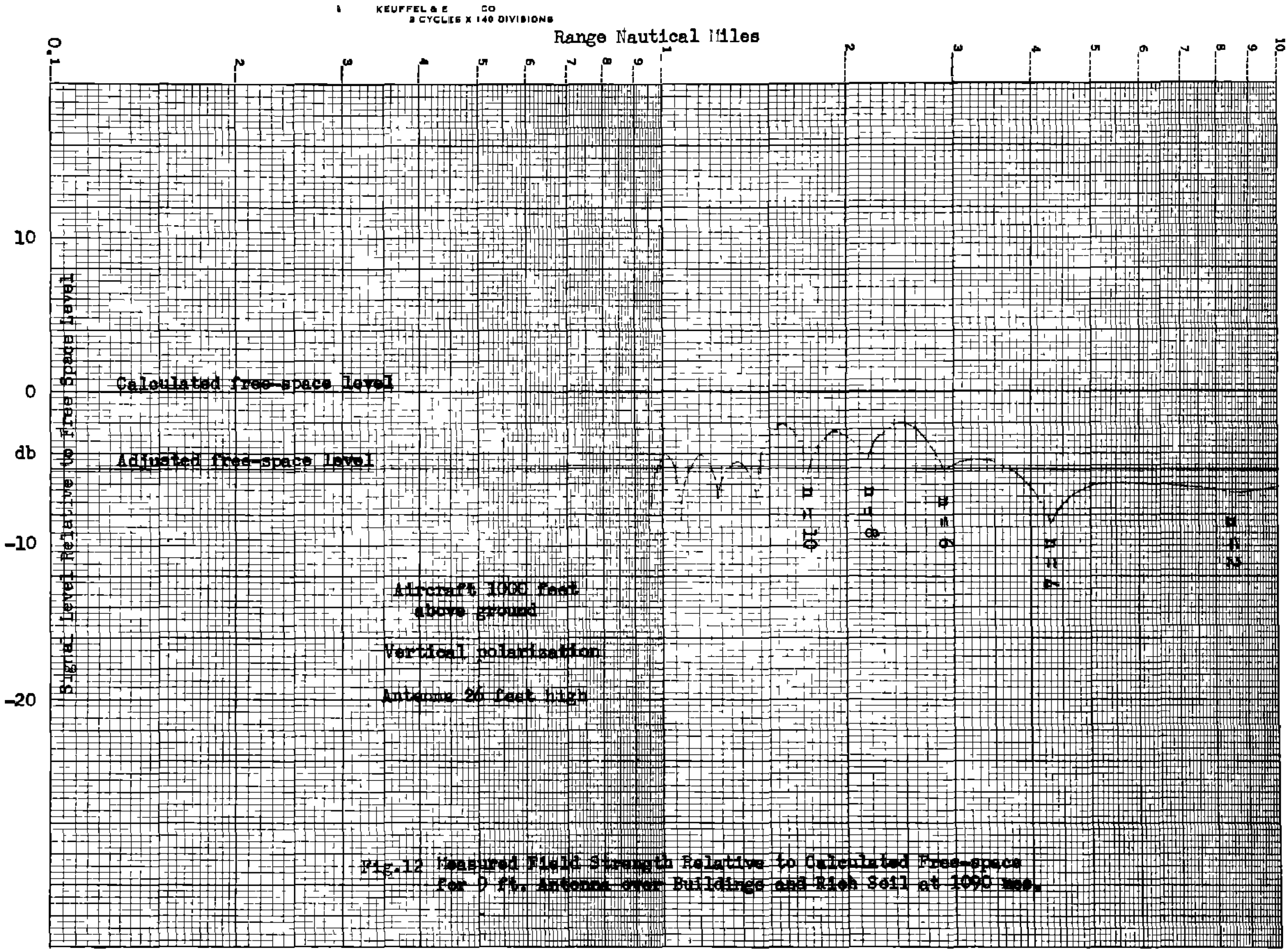


Fig.12 Measured Field Strength Relative to Calculated Free-space for 0 ft. Antenna over Buildings and Rich Soil at 1090 mcs.

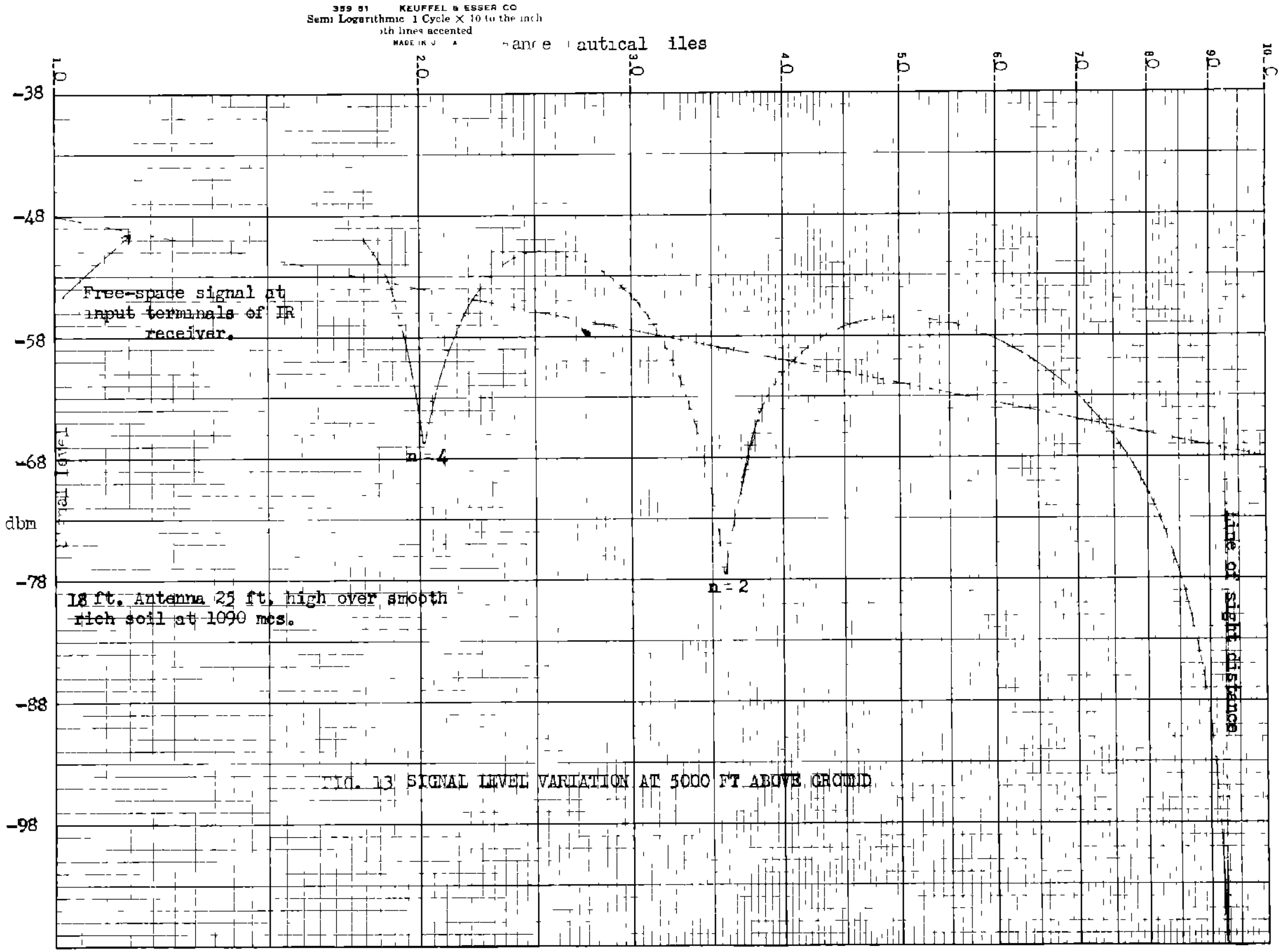
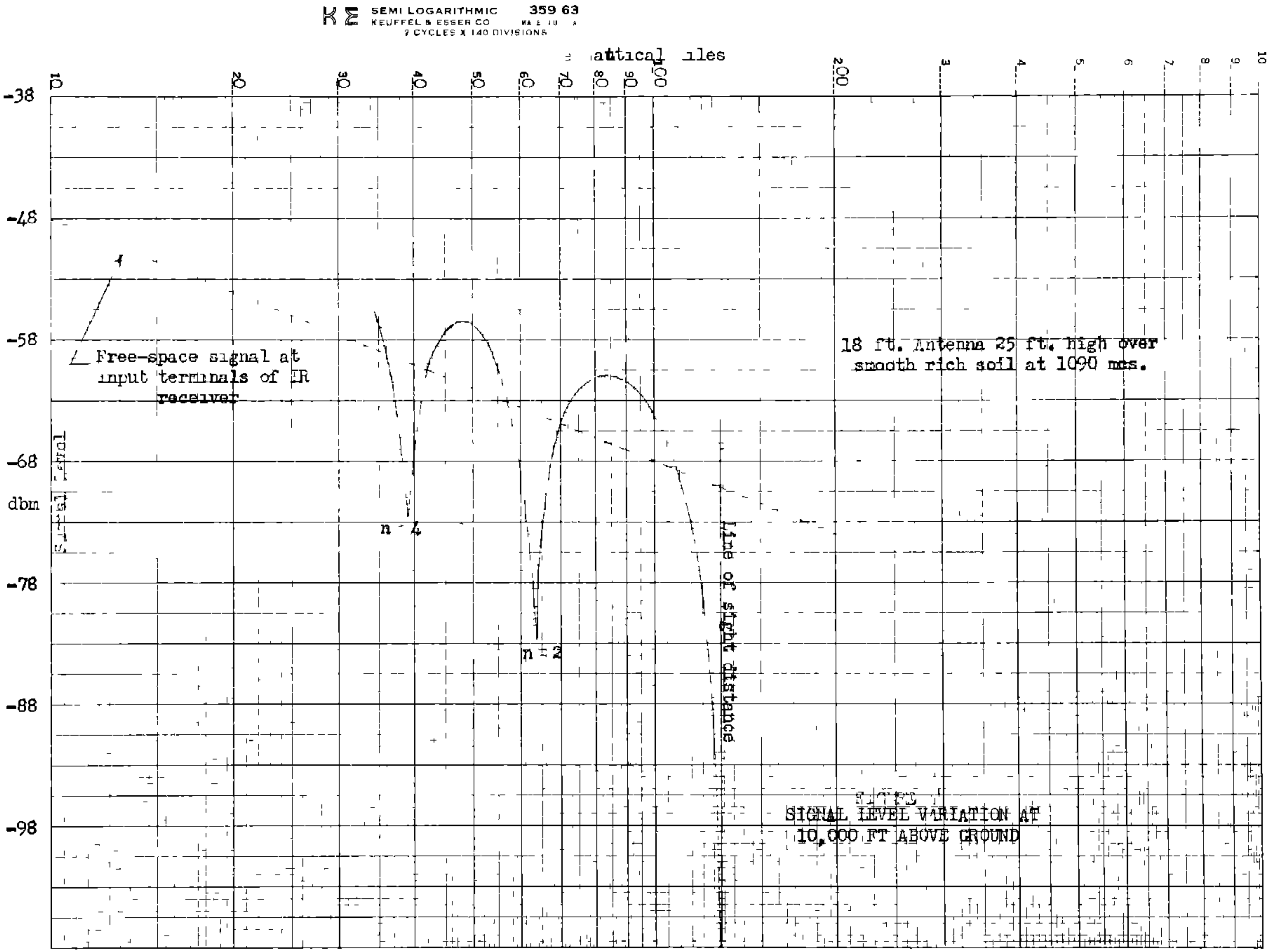


FIG. 13 SIGNAL LEVEL VARIATION AT 5000 FT ABOVE GROUND



K E SEMI LOGARITHMIC 359 63
KEUFFEL & ESSER CO.
7 CYCLES X 140 DIVISIONS
-38
-48
-58
-68
dbm
-78
-88
-98
10
20
30
40
50
60
70
80
90
100
200
3
4
5
6
7
8
9
10
Free-space signal at input terminals of IR receiver
n = 4
n = 2
Line of sight distance
18 ft. Antenna 25 ft. high over smooth rich soil at 1090 mcs.
SIGNAL LEVEL VARIATION AT 10,000 FT ABOVE GROUND

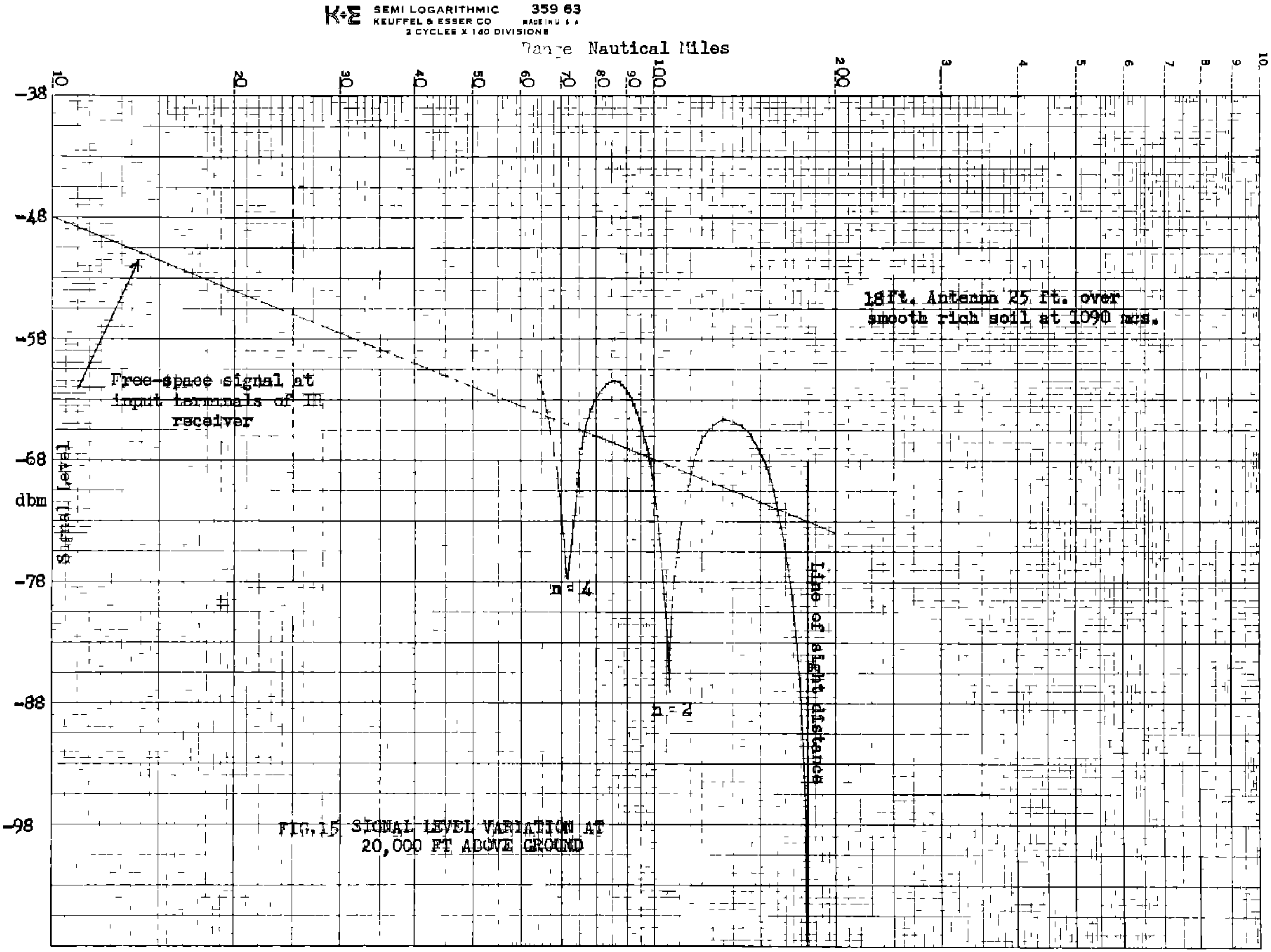


FIG. 15 SIGNAL LEVEL VARIATION AT 20,000 FT ABOVE GROUND

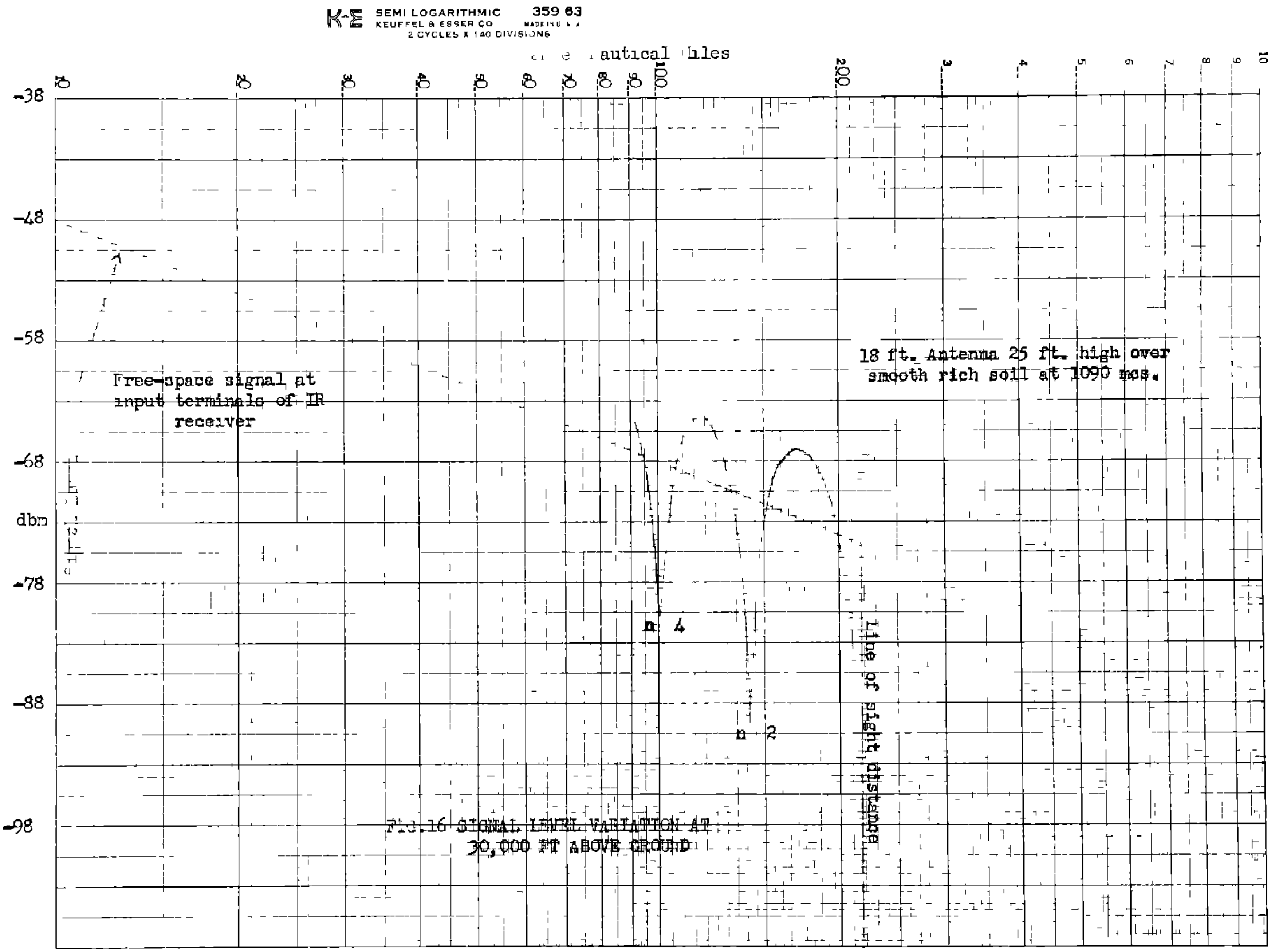
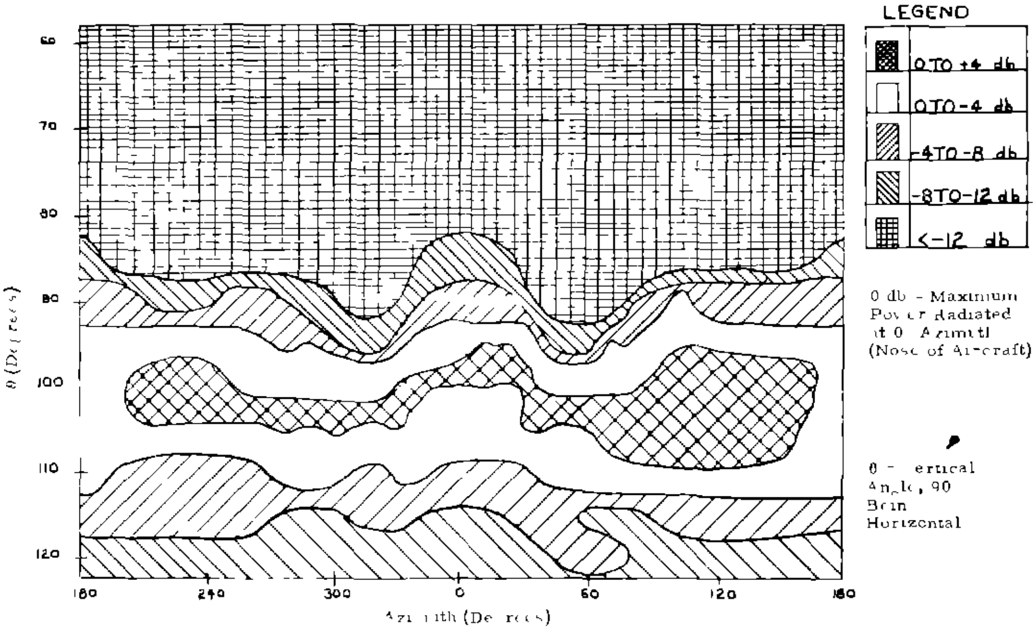
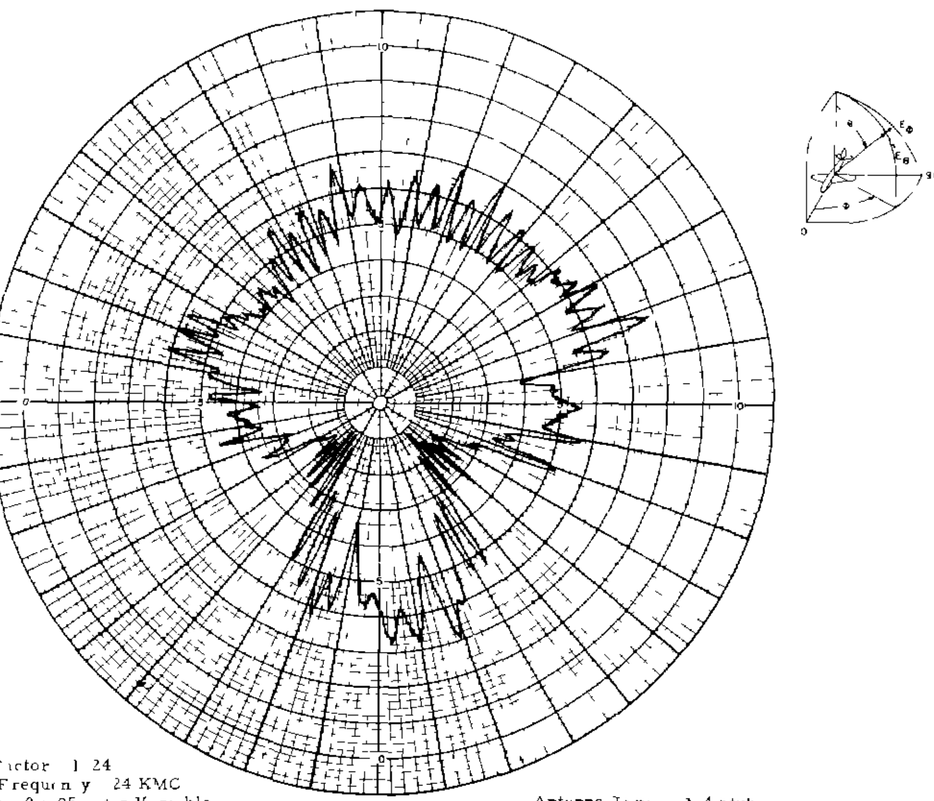


Fig. 16 SIGNAL LEVEL VARIATION AT 30,000 FT ABOVE GROUND



(A) Contour Map



(B) Polar Plot

FIG. 17 RADIATION PATTERN OF λ/4 STUB ANTENNA ON BELLY ON ℄ OF WINGS OF A DC-3

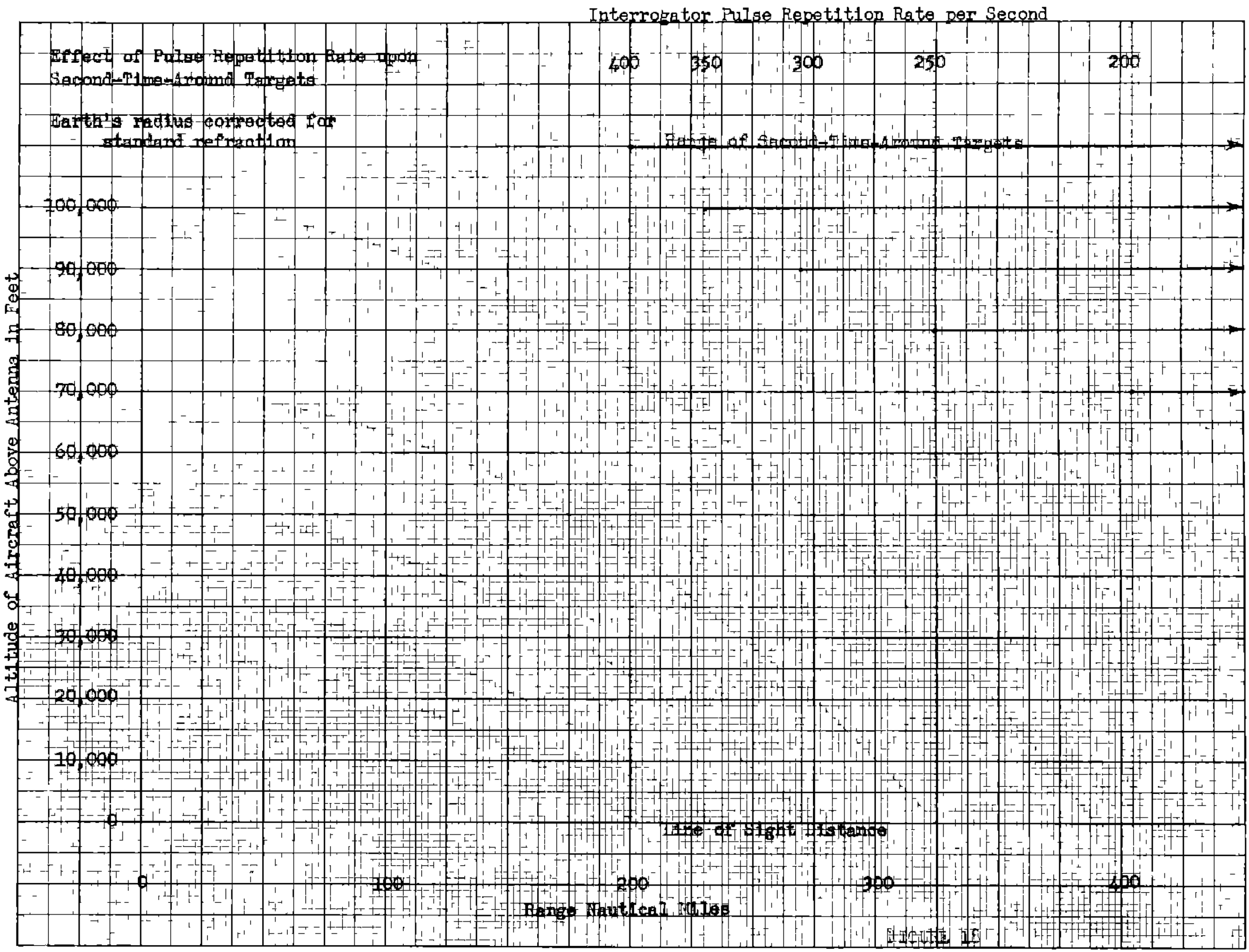

Interrogator Pulse Repetition Rate per Second
Effect of Pulse Repetition Rate upon
Second-Time-Around Targets
Earth's radius corrected for
standard refraction
400
350
300
250
200
Range of Second-Time-Around Targets
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Altitude of Aircraft Above Antenna in Feet
Line of Sight Distance
0
100
200
300
400
Range Nautical Miles

FIGURE 19

IT Transmitter Frequency Mcs.	Transponder Receiver Frequency Mcs.	Required Transponder Receiver RF Bandpass Mcs.
1030 ± 0.1	1030 ± 1	3.7
	± 2	5.7
	± 2.5	6.7
	± 3	7.7
	± 4	9.7
1030 ± 0.5	1030 ± 1	4.5
	± 2	6.5
	± 2.5	7.5
	± 3	8.5
	± 4	10.5
1030 ± 1	1030 ± 1	5.5
	± 2	7.5
	± 2.5	8.5
	± 3	9.5
	± 4	11.5
1030 ± 2	1030 ± 1	7.5
	± 2	9.5
	± 2.5	10.5
	± 3	11.5
	± 4	13.5

Fig. 19 Interrogation Path Frequency Tolerances
Based on Minimum RF Bandpass of 1.5 Mcs. for 1 usec Pulse

Transponder Transmitter Frequency cs.	IR Receiver Frequency cs.	Required IR Receiver RF Bandpass cs.
1090 $\pm$ 1	1090 $\pm$ 0.1	9.2
	$\pm$ 0.5	10
	$\pm$ 1.0	11
	$\pm$ 2.0	13
1090 $\pm$ 2	1090 $\pm$ 0.1	11.2
	$\pm$ 0.5	12
	$\pm$ 1.0	13
	$\pm$ 2.0	15
1090 $\pm$ 2.5	1090 $\pm$ 0.1	12.2
	$\pm$ 0.5	13
	$\pm$ 1.0	14
	$\pm$ 2.0	16
1090 $\pm$ 3	1090 $\pm$ 0.1	13.2
	$\pm$ 0.5	14
	$\pm$ 1.0	15
	$\pm$ 2.0	17

Fig. 20 Reply Path Frequency Tolerances Based on
Minimum RF Bandpass of 7 cs. for a 0.1 usec Pulse Rise Time

IR Output Power Watts	Transponder Sensitivity dbm	Free-Space Propagation: Interrogation Range Nautical Miles Minimum	Maximum	Side Lobe Interrogation Range Nautical Miles Minimum	Maximum	Interference Pattern over Smooth Soil: Interrogation Range Nautical Miles Minimum	Maximum	Side Lobe Interrogation Range Nautical Miles Minimum	Maximum
1000	-74 ± 0 db	294	294	18.6	18.6	33	524	2.08	33
	± 1 db	262	330	16.5	20.8	29.4	586	1.86	37.1
	± 2 db	233	371	14.8	23.4	26.2	656	1.65	41.5
	± 3 db	208	415	13.2	26.2	23.3	738	1.48	46.5
	± 4 db	186	465	11.7	29.4	20.8	825	1.32	52.4
	± 5 db	165	524	10.4	33.1	18.6	928	1.17	58.6
	± 6 db	147	586	9.3	37	16.5	1040	1.04	65.6
1500	-74 ± 0 db	362	362	22.8	22.8	40.6	645	2.57	40.6
	± 1 db	323	406	20.3	25.6	36.2	702	2.29	45.5
	± 2 db	287	455	18.1	28.7	32.3	810	2.03	51.1
	± 3 db	257	511	16.1	32.2	28.7	906	1.81	57.2
	± 4 db	229	572	14.4	36	25.7	1020	1.61	64.5
	± 5 db	203	645	12.8	40.6	22.8	1140	1.44	72
	± 6 db	181	720	11.4	45.4	20.3	1280	1.28	81
2000	-74 ± 0 db	415	415	26.2	26.2	46.5	738	2.94	46.5
	± 1 db	370	465	23.3	29.4	41.5	825	2.62	52.4
	± 2 db	330	524	20.8	33.1	37	928	2.33	58.6
	± 3 db	294	586	18.6	37	33	1040	2.08	65.6
	± 4 db	262	656	16.5	41.5	29.4	1170	1.86	73.8
	± 5 db	233	738	14.7	46.5	26.2	1315	1.65	82.5
	± 6 db	208	825	13.1	52.3	23.3	1470	1.47	92.8

Effect of Power and Sensitivity Tolerances upon Interrogation Range. 18 ft. Antenna Side Lobes -24 db. Interference Pattern Lobes 5 db and Nulls -19 db from Free-Space.

Fig. 21

Transponder Output Power Watts	IR Receiver Sensitivity	Signal Increase over Free-Space for Side Lobe Breakthrough on PPI	Signal Decrease Below Free-Space for Target Fade
500 ± 0 db	-84 dbm ± 0 db	11 db	-10 db
	± 1 db	10 db	-9 db
	± 2 db	9 db	-8 db
	± 3 db	8 db	-7 db
500 ± 1 db	-84 dbm ± 0 db	10 db	-9 db
	± 1 db	9 db	-8 db
	± 2 db	8 db	-7 db
	± 3 db	7 db	-6 db
500 ± 2 db	-84 dbm ± 0 db	9 db	-8 db
	± 1 db	8 db	-7 db
	± 2 db	7 db	-6 db
	± 3 db	6 db	-5 db
500 ± 3 db	-84 dbm ± 0 db	8 db	-7 db
	± 1 db	7 db	-6 db
	± 2 db	6 db	-5 db
	± 3 db	5 db	-4 db
500 ± 4 db	-84 dbm ± 0 db	7 db	-6 db
	± 1 db	6 db	-5 db
	± 2 db	*5 db	-4 db
	± 3 db	*4 db	-3 db

*Side lobes will break through on PPI due to pattern lobes

Fig. 2[illegible] Effect of Reply Path Power and Sensitivity Tolerances on Target Display. 18 ft. Antenna Side Lobes -24 db.

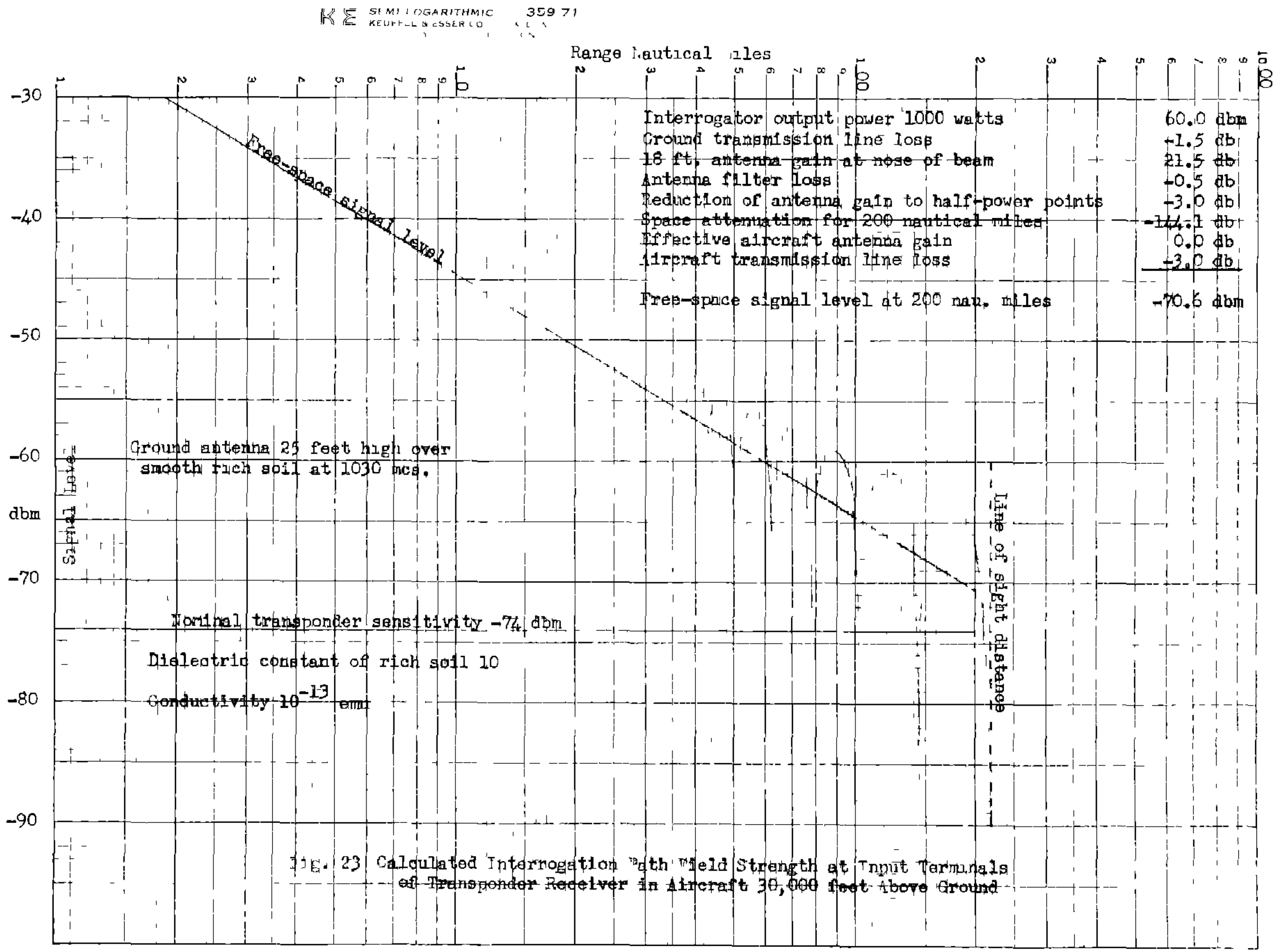


Fig. 23 Calculated Interrogation Path Field Strength at Input Terminals of Transponder Receiver in Aircraft 30,000 feet Above Ground

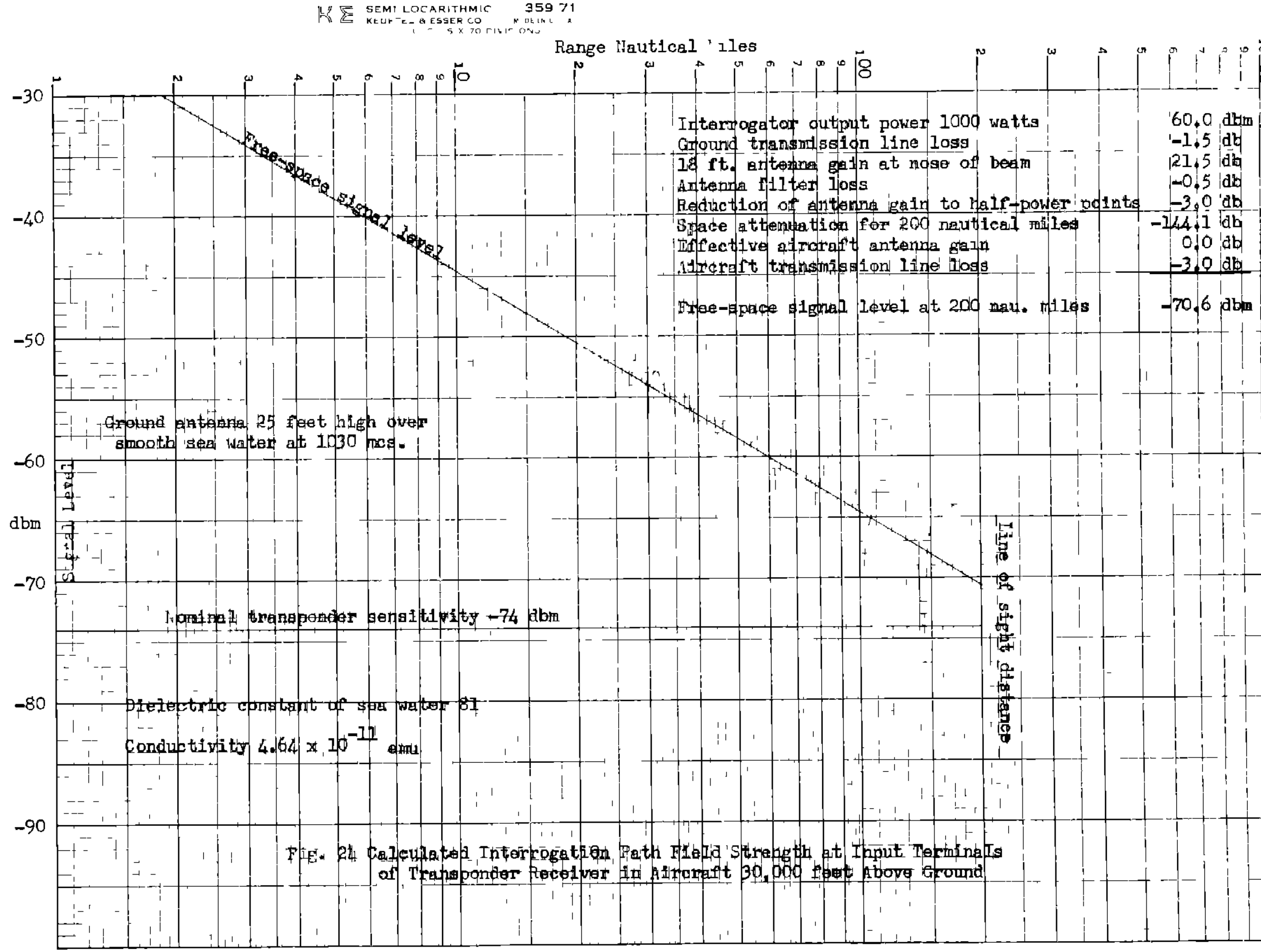
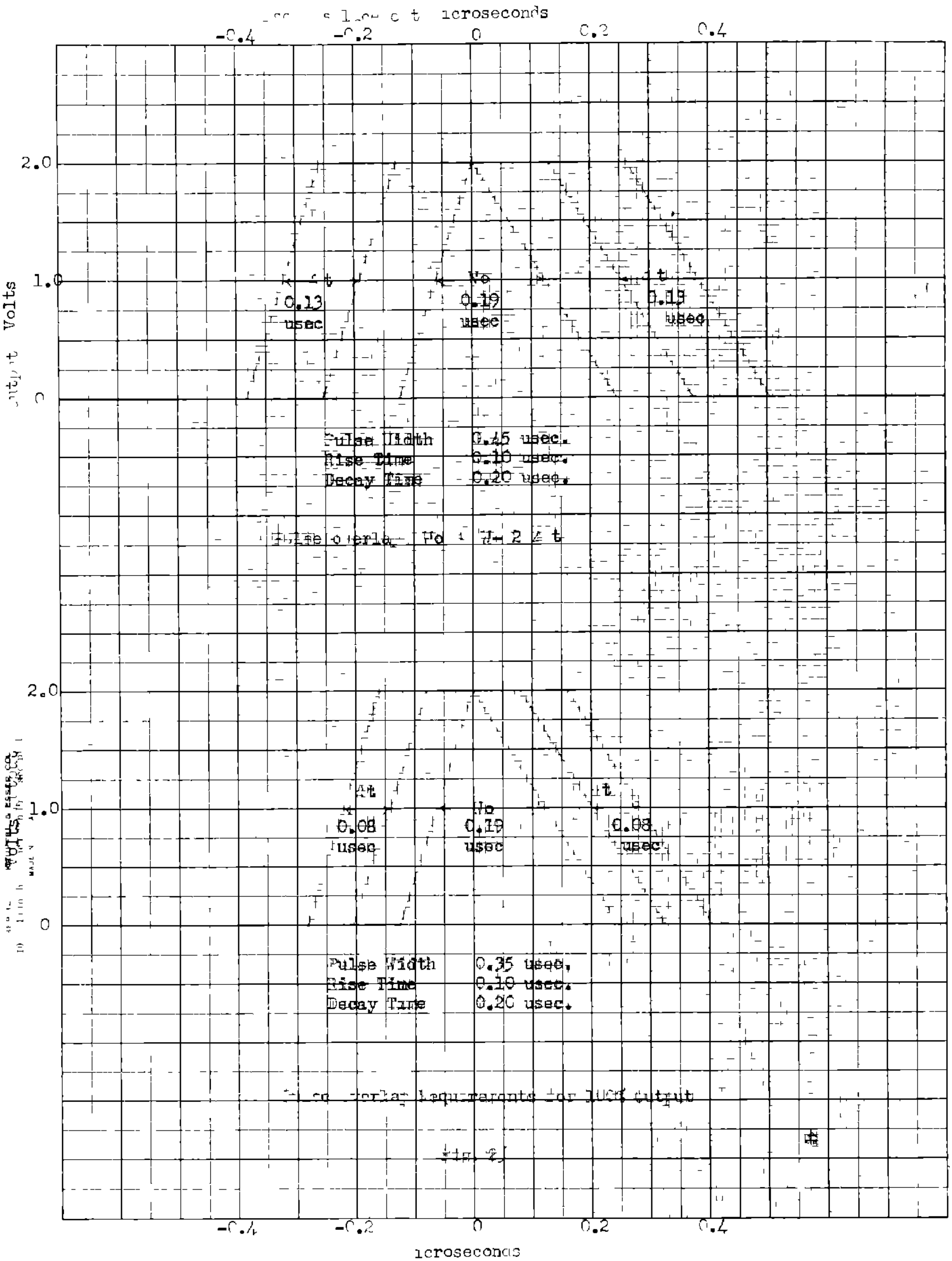


Fig. 24 Calculated Interrogation Path Field Strength at Input Terminals of Transponder Receiver in Aircraft 30,000 feet Above Ground



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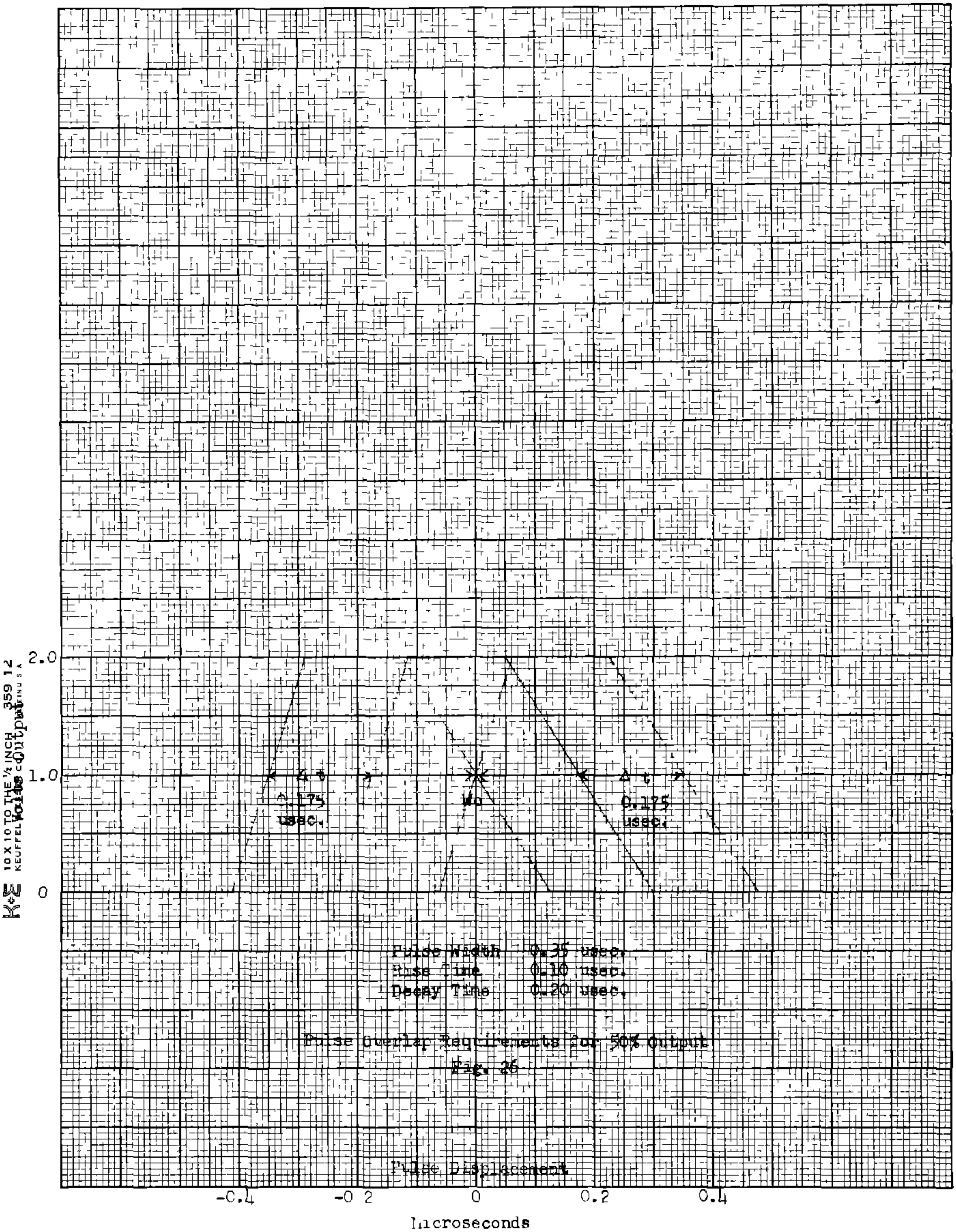

Pulse Overlap Requirements for 50% Output
Fig. 26

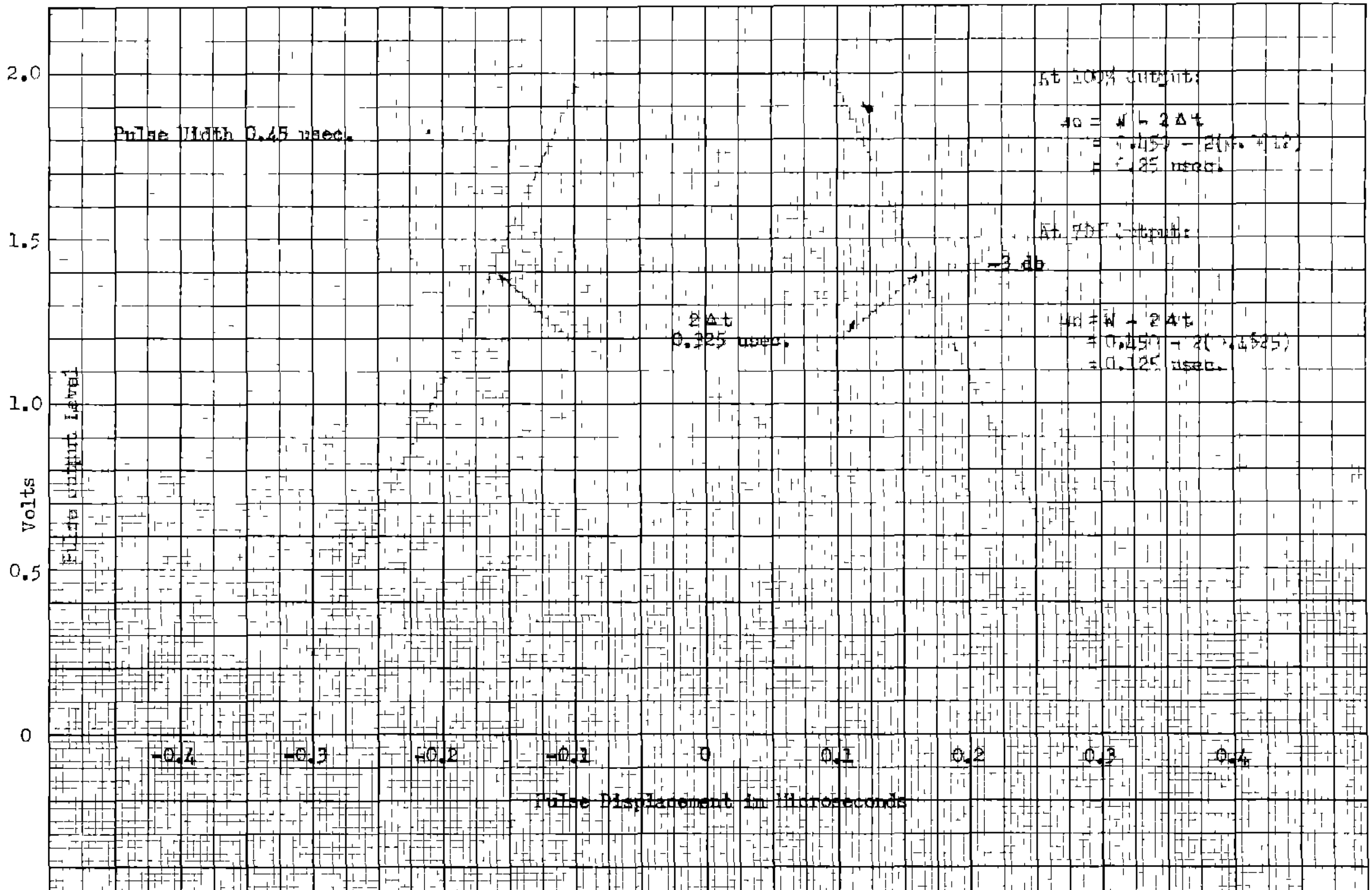

Fig. 27 Measured Coincidence Curve for Two Sliding Pulses on Video Interconnection Equipment 2.3USAa

	Video Interconnect Equipment * ANDB 2.3 84a	Future Improved Decoders		Perfect Decoder and Ground Equipment ***
		70% OUTPUT		
Minimum Pulse Overlap usec.	0.125	0.10		0.078
Total System Tolerance usec.	±0.1125	±0.13		±0.136
Total Airborne Tolerance		*	**	
2-pulse Code	±0.087	±0.12	±0.13	±0.136
4-pulse Code	±0.072	±0.097	±0.10	±0.112
8-pulse Code	±0.064	±0.086	±0.09	±0.101
15-pulse Code	±0.06	±0.08	±0.08	±0.095
		50% OUTPUT		
Minimum Pulse Overlap usec.	0.03	0.015		≥0
Total System Tolerance usec.	±0.16	±0.168		±0.175
Total Airborne Tolerance		*	**	
2-pulse Code	±0.148	±0.162	±0.168	±0.175
4-pulse Code	±0.107	±0.12	±0.124	±0.135
8-pulse Code	±0.087	±0.10	±0.104	±0.12
15-pulse Code	±0.076	±0.09	±0.093	±0.11

Pulse Width 0.35 usec Rise Time 0.10 usec. Decay Time 0.20 usec.

* Total Ground Equipment Tolerance ± 0.1 usec.
** Total Ground Equipment Tolerance ±0.05 usec.
*** Zero Tolerance Ground Equipment

MAXIMUM PULSE TOLERANCES

Fig. 28

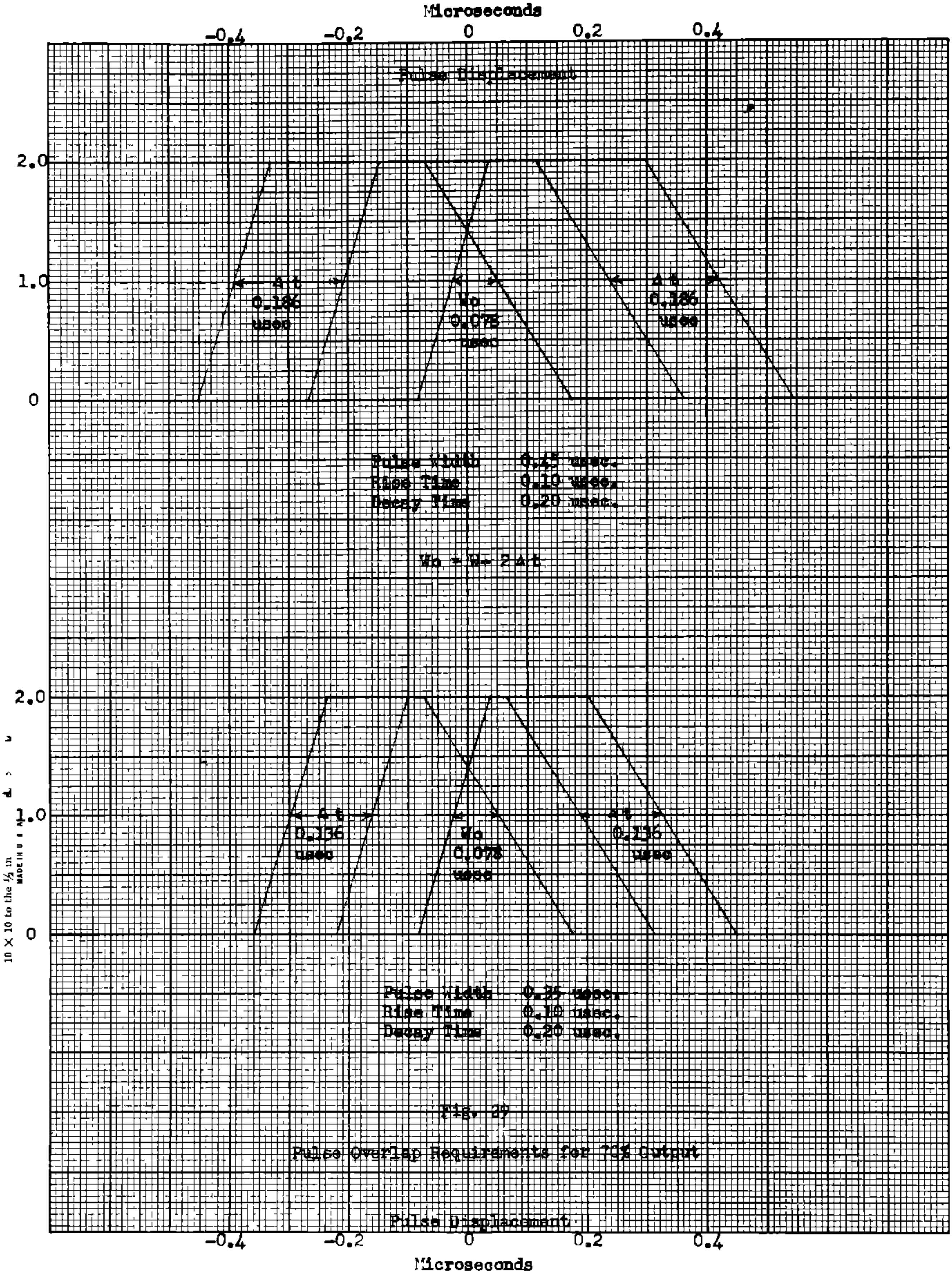

Fig. 29

Pulse Overlap Requirements for 70% Output

Pulse Width W μsec.	Required Decoder Overlap Wo μsec.	Maximum System Tolerance Δt μsec.	Coincidence Selectivity μsec.
0.35	0.25	≮ 0.05	0.2
	0.19	0.08	0.32
	0.125	0.113	0.45
	0.078	0.136	0.544
0.45	0.25	≮ 0.1	0.4
	0.19	0.13	0.52
	0.125	0.163	0.65
	0.078	0.186	0.744
0.55	0.25	≮ 0.15	0.6
	0.19	0.18	0.72
	0.125	0.213	0.85
	0.078	0.236	0.944

$$\Delta t = \frac{W - W_o}{2}$$

Pulse Width W μsec.	Killer Tap Selectivity Ws μsec.	Decoder Killer Selectivity Wk μsec.
0.35	0.1	0.45
	0.2	0.55
	0.4	0.75
	0.6	0.95
	0.8	1.15
0.45	0.1	0.55
	0.2	0.65
	0.4	0.85
	0.6	1.05
	0.8	1.25
0.55	0.1	0.65
	0.2	0.75
	0.4	0.95
	0.6	1.15
	0.8	1.35

$$W_k = W + W_s$$

Fig. 30

Effects of Pulse Width and Decoder Overlap Upon System Tolerance and Selectivity

Decoder Killer Selectivity μsec.	Percent Killed Replies in Garbled Zone			
		Average	Future System Expansion	
	Code 00	All Codes	Maximum	Average
0.2	6.9	5.29	12.7	9.77
0.3	10.3	7.93	19.1	14.6
0.4	13.8	10.6	25.4	19.5
0.5	17.25	13.2	31.9	24.4
0.6	20.7	15.9	38.2	29.3
0.7	24.1	18.5	44.6	34.2
0.8	27.6	21.2	50.9	39.0
0.9	31.0	23.0	57.3	43.9
1.0	34.5	26.4	63.7	48.8
1.1	37.9	29.1	70.1	53.7
1.2	41.4	31.7	76.4	58.6
1.3	44.8	34.4	82.8	63.4

Fig. 31

Effect of Decoder Killer Selectivity Upon Percentage of Killed Replies in Garble Zone