

NATIONAL BUREAU OF STANDARDS REPORT

1826

**Preliminary Report on Propagation Measurements
From 92 - 1046 Mc at Cheyenne Mountain, Colorado**

by

G. R. Chambers, J. W. Herbstreit, and K. A. Norton



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PRELIMINARY REPORT ON PROPAGATION MEASUREMENTS
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By

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PRELIMINARY REPORT ON PROPAGATION MEASUREMENTS
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G. R. Chambers*, J. W. Herbstreit**, and K. A. Norton**
National Bureau of Standards

Acknowledgments

Special mention should be made of the extensive contributions of J. H. Chisholm to this project. Mr. Chisholm was responsible for most of the details of planning connected with the choice of transmitting and receiving sites and the choice and design of the 1000-Mc transmitting and receiving equipment; he was the leader of the group responsible for the procurement, installation and operation of the 1000-Mc system and remained with the project through November, 1951, at which time preliminary observations had been made on 1000-Mc out to distances of several hundred miles. The other professional personnel who are now or have been associated with this project are: Alfred F. Barghausen, Albrecht Barsis, John R. Burgener, Martin T. Decker, A. J. Estin, John R. Gozinsky, K. O. Hornberg, H. B. Janes, Leo J. Maloney, Raymond E. McGavin, Sanford B. Schwartz, Glenn A. Scharp, Andrew Walters and Paul I. Wells.

Abstract

A description is given of the facilities provided by the National Bureau of Standards on Cheyenne Mountain in Colorado and in its vicinity which are used for the measurement of the transmission loss on radio transmission circuits operated in the frequency range from 92 to 1046 Mc. Some preliminary results of these measurements are presented together with tentative theoretical explanations.

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SUMMARY

This summary is intended to be sufficiently extensive so that those not interested in the details may nevertheless obtain a comprehensive review of the work going on at Cheyenne Mountain, Colorado, near Colorado Springs.

An essential part of any radio system of communication, navigation, or remote control is the propagation between the transmitting and receiving antennas. The most significant measure of the characteristics of this part of a system is a parameter we shall call the "transmission loss," that is, the ratio of the power radiated from the transmitting antenna to the resulting signal power available from the receiving antenna. The transmission loss depends upon (1) the gain characteristics of the transmitting antenna, (2) the characteristics of the terrain between the transmitting and receiving antennas (except in the very special case of the transmission between aircraft separated by a distance much less than their altitude above the ground), (3) the characteristics of the atmosphere between the transmitting and receiving antennas, and (4) the gain characteristics of the receiving antennas.

Since the characteristics of the terrain and the atmosphere vary extensively with geographical location, the National Bureau of Standards has been conducting and coordinating an extensive program for the measurement of transmission loss in various parts of the United States. An indication of the extent of this cooperative program may be obtained from figure 1, which gives the locations of the transmission paths under study. On transmission paths greater than, say, 40 miles in length, the variability from minute to minute in the characteristics of the atmosphere along the path causes the transmission loss to vary over wide ranges. A proper assessment of the importance of this fading to the operation of a radio system can be obtained only by recording the transmission loss over an extended period of time. In general it is believed that a minimum of one year's recordings is essential for such an assessment. Examples of the appearance of this fading at points far beyond the radio horizon are shown on figures 21, 33, 36 and 37. Statistical analyses of the fading observations on the paths originating from Cheyenne Mountain transmitters are shown on figures 28, 29, 30, 31 and 32.

In anticipation of the development and extensive use of the frequency band 890-1600 Mc for air navigation systems involving air-to-ground transmission paths, the Air Navigation Development Board is supporting an extension of the NBS radio propagation research program into this frequency region and under terrain conditions intended to represent, as closely as possible, typical

air-to-ground transmission paths. The primary purpose of this report is to provide a detailed description of the physical facilities provided by the NBS to make possible this extension of the program. Typical ground terminals of air-to-ground transmission paths consist of comparatively low antennas, say 30 feet above local terrain, located on comparatively flat terrain. Figures 5 and 7a illustrate examples of sites chosen to simulate an actual ground terminal. Since the object of the transmission-loss measurements was the recording of signals over long periods of time, the actual use of an aircraft as the air terminal was considered to be impracticable. Instead, two sites were chosen on Cheyenne Mountain which are believed to simulate satisfactorily the characteristics of typical air terminals several thousand feet above the local terrain. These sites are shown on figures 3 and 4, and their relation to the terrain along the transmission paths presently in use is shown on figures 6, 26, 38, 42 and 43.

Because of its great cost it was decided to use only a single UHF transmitter, and this, operating at 1046 Mc, was located on the higher of the two sites, the transmitting antenna being at a height of 8760 feet above sea level. With the assistance of the United States Army Signal Corps who also have a vital interest in radio propagation information in the VHF and UHF portion of the spectrum, four other transmitters were provided in the Cheyenne Mountain program, operating on frequencies of 92, 100, 192.8 and 210.4 Mc, and their operation provides a means of extrapolating the results of the 1046-Mc observations to other frequencies and then indirectly to the other transmission paths shown on figure 1 which have a much wider variety of terminal heights and climatological characteristics. Descriptions of these five transmitters are given on figures 9, 10, 11, 12, 13 and 14.

In order to extend the range of the transmission-loss measuring system very narrow-band receivers were employed - approximately 500 cycles per second bandwidth - and very precise crystal control of the transmitter and receiver oscillators was used to make this feasible. The receivers used have a high degree of gain and noise-figure stability and are described in some detail on figures 15, 16, 17, 18, 19 and 20.

The ability to predict the 1046-Mc transmission loss and its variability expected for a wide variety of transmission paths is obviously essential to a prediction of the range and reliability of radio systems operating in this part of the frequency spectrum. For example, if it is known that P_0 is the minimum power from the receiving antenna (expressed in $^{\circ}$ decibels above one watt) necessary to provide satisfactory service in a given system, then the transmitter power (in decibels above

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one watt) required to provide satisfactory service for p percent of the time is equal to $L(p) + P_0$, where $L(p)$ denotes the transmission loss (in decibels) exceeded for $(100 - p)$ percent of the time. Figures 29 and 30 give $L(p)$ as a function of p based on our preliminary data.

The geographical spacing between systems, operating in the same or in adjacent parts of the spectrum, required for the elimination of mutual interference, is a function not only of the transmission losses expected with each system but also depends on the correlation between the variations in these two transmission losses. Discussions of this, and other applications, of our data are not contained in this report but will be included in later reports. It is believed that such questions can be treated satisfactorily only with respect to particular systems for which all of the pertinent parameters are specified.

An extensive theoretical discussion of within-line-of-sight propagation is given in Section VII of this paper. This shows the degree to which transmission loss is calculable at points within the line of sight. It is shown, in particular, that the terrain within line of sight of the lower of the two antennas in a system will affect the expected transmission loss. This means, for example, with a ground antenna at a height of 30-35 feet, that the character of the terrain within a radius of about 8 miles of this antenna may be expected to affect the performance of the system for all transmission paths within the line of sight. Furthermore, a criterion of roughness is given indicating the deviations from a smooth spherical surface which are permissible within this horizon distance in order to make possible the accurate calculation of the expected transmission loss. It is interesting and significant to note that the terrain in the vicinity of the Kendrick site (see figure 5) was not sufficiently smooth to satisfy this criterion at 1046 Mc nor even, for that matter, at 92 Mc. Although the information available supports the validity of the theory, it will be necessary to collect extensive additional experimental data in order to obtain a more complete appreciation of its significance.

Progress has recently been made also in the development of a theory of propagation to points far beyond the horizon of the transmitting antenna. The data plotted in figure 24 for this far region indicate a much lower rate of attenuation with distance than was expected in previous estimates, while figure 25 indicates the degree of success achieved in explaining these results by means of the Fein²stein theory of partial reflection recently developed at the NBS. Figures 26, 27, 34 and 35 provide information of use in the interpretation and application of this new theory.

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I. INTRODUCTION

The National Bureau of Standards Cheyenne Mountain Field Station at Colorado Springs, Colorado, has been established to supply radio propagation information which closely approximates transmissions from an aircraft to distances far beyond the horizon. Information is being obtained in such a way that results advance our over-all knowledge of the factors influencing radio propagation in other parts of the world and in other radio systems not immediately under study.

At the close of World War II, considerable effort was being made in the air navigation field to develop a unified system of air communications and navigation in the frequency range 960 to 1600 Mc. This work is now centralized in the Air Navigation and Development Board which is administratively under the Civil Aeronautics Administration.

Very little quantitative information exists relative to the effects of irregular terrain for transmission paths within the radio line of sight and still less at distances beyond the usual service range of navigational systems where signals would be a source of interference to nearby facilities operating on the same or adjacent frequency channels.

In order to expedite the program of research in tropospheric propagation which is designed to determine propagation factors required for effective allocation and use of VHF and UHF frequency bands, particularly from an air navigation standpoint, the Air Navigation and Development Board has been sponsoring a rapid expansion of the tropospheric propagation research facilities of the National Bureau of Standards at Cheyenne Mountain, including the development, installation and operation of a system for studying propagation factors at approximately 1000 Mc. This system utilizes a transmitter which gives the highest continuous power output of any 1000-Mc transmitter ever developed in this country and specially developed very narrow bandwidth receivers capable of measuring received signal powers much lower than usual receivers for this frequency range. This high level of system performance is necessary to obtain radio propagation data at great distances.

The United States Army Signal Corps, because of their vital need for radio propagation information in the VHF and UHF frequency bands, have also been sponsoring the acceleration and expansion of research facilities at Cheyenne Mountain. Military personnel of the Signal Corps are participating in the work and are receiving training in the methods of making VHF and UHF radio propagation measurements.

The Cheyenne Mountain measurements at frequencies between 92 and 210.4 Mc, which are not in the proposed air-navigation band, provide a means of studying climatic effects on tropospheric propagation in Colorado and vicinity, for comparison with many other regions of the country where measurements have been made at these presently-used air-navigation communications, FM and television frequencies. A high system performance in the range 92-210.4 Mc has been achieved through the use of stabilized transmitters, relatively high antenna gains and very narrow-band receivers.

A picture of the over-all VHF-UHF tropospheric field strength program of the National Bureau of Standards may be obtained from figure 1. This shows the numerous propagation paths over which VHF and UHF field strengths are being measured.

II. SYSTEM SELECTION

When the National Bureau of Standards was requested to accelerate its tropospheric propagation research program, a complete study of existing facilities and equipment was initiated. System design, selection of a suitable site, and establishment of the Cheyenne Mountain Field Station followed. Some of the most important factors concerned with the selection of the Cheyenne Mountain location and and system design employed are as follows:

A. Site

It was proposed to locate a site and install a system for long-term continuous radio-propagation measurements over air-to-ground paths near and below the horizon. Use of aircraft for one terminal was considered prohibitively expensive and impractical for long-term continuous recording; moreover, their use would not permit the obtaining of data under extremes of weather conditions. For these reasons, ground installations which would simulate an air-to-ground path were sought. Accordingly, after an extensive survey, a site on Cheyenne Mountain near Colorado Springs, Colorado, was chosen. This mountain, 9200 feet above sea level, rises abruptly out of the eastern Colorado plains and provides an excellent "airborne terminal" which is over 3000 feet above the adjacent plains. The existing all-weather road and high-voltage power

facilities to the mountain summit were also important factors to be considered. Receiving sites and paths with almost any desired characteristics were available at the distances of interest, including smooth, moderately rough and rough terrain, as well as some of the most rugged terrain in North America. In addition, highway systems extending eastward into Colorado, Kansas, and Arkansas, offered a number of approximately radial all-weather highways, suitable for mobile recordings and convenient to fixed recording sites. The location of the Army's Camp Carson and the Air Force installation at Peterson Field in Colorado Springs were considered as making future aircraft investigations and measurements practical.

B. Equipment

The primary objective of these experiments was an investigation of radio fields produced near and far beyond the horizon. This required a receiving and recording system embodying maximum sensitivity, accurate monitoring of performance, accurate calibrations and a minimum of variations over extended operating periods. From a propagation research point of view, the absence of suitable available equipment in the 92-1600-Mc range has been fortunate, since it made possible the design and development of a system specifically suited for propagation measurements rather than the usual compromise adaptation of existing commercial or military equipment. The system sensitivity of a number of experimental methods was analyzed and comparisons made on the basis of a "Margin of Detectability", M . This was calculated in db below the free-space value for radio waves propagated over a path arbitrarily taken to be 200 miles long. M is the excess of the free-space power at this distance over the minimum detectable power and is expressed by the following formula:

$$M \text{ (db)} = P_t - L_t - L_r - L_f - P_m, \quad (1)$$

where: $L_f = 20 \log_{10} (4\pi d/\lambda) - G_t - G_r, \quad (2)$

$$P_m = 10 \log_{10} (\rho f k T B), \quad (3)$$

- P_t = average transmitter power delivered to the transmitting antenna transmission line, expressed in db above one watt,
- L_t, L_r = transmission line, antenna and coupling circuit ohmic losses at the transmitter and receiver, respectively expressed in db,
- L_f = transmission loss expressed in db expected for transmission through free space to a distance, (d), expressed in wavelengths (λ),
- G_t, G_r = gains of the transmitting and receiving antennas (relative to an isotropic antenna) expressed in db,
- P_m = minimum detectable signal in the presence of receiver noise, expressed in db above one watt,
- f = receiver noise figure,
- k = Boltzman's constant = 1.37×10^{-23} joules per degree K,
- T = absolute temperature taken to be 300° K,
- B = equivalent noise bandwidth of the receiver in cycles per second,
- ρ = minimum detectable ratio of signal power to noise power that can be measured by the detection circuits and is a function of (1) signal and noise bandwidths, (2) modulation (i.e., for pulses, the pulse width, pulse repetition frequency), (3) detector characteristics, (4) gating and band-sweeping techniques, (5) receiver-gain stability, and (6) receiver noise-figure stability. Detailed treatment of some of these factors can be found in the literature. 1,2/*

A study of narrow-band sweeping circuits to improve sensitivity, made at Central Radio Propagation Laboratory by J. W. Herbstreit and W. Q. Crichlow, was used in the analysis of the cw systems. Further studies of this problem are being made at the present time, but, tentatively, such circuits have been rejected as unsuitable for our present application.

* See references at the end of this report.

For the purposes of our present analysis, the antenna gains may be treated as constants in the above equation. Similarly, the receiver noise figure (f) can be considered invariable for a particular frequency and, at 200 miles, the distance in wave lengths (d/λ) is also constant. Current research on receiver noise figures in the 1000-Mc range did not promise any substantial reduction from the 8-10-db noise figures of good 1000-Mc receivers and 10 db is therefore considered a practical constant. At VHF somewhat better noise figures can be obtained; at any one frequency, however, this is also assumed to be constant. The loss terms L_r and L_t can be made to approach unity by careful design and avoidance of long transmission lines. Lumping all these relatively constant parameters into one constant transmission loss K_A :

$$M \text{ (db)} = K_A + P_t - 10 \log_{10} B - 10 \log_{10} \rho \quad (4)$$

From this abbreviated relationship it can be seen that choosing a system is reduced primarily to choosing average power output, bandwidths, and threshold-detection factors. It is clear from equation (4) that the use of a system with the highest available average power and the narrowest feasible bandwidth will provide the largest margin of detectability. In addition to theoretical considerations, practical operating problems and costs were significant factors in determining a final system, since the ultimate objective was continuous 24-hour-per-day operation at all frequencies. Available high-power tubes in the 1000-Mc range consisted of three major types: (1) magnetron, (2) klystron, and (3) resnatron. An average continuous-wave power output of at least 1 to 5 kw was available in these tubes. A peak pulse power of several megawatts was available in klystron tubes having approximately the same average power as the cw tubes. Pulse-modulated transmitters producing several megawatts peak power, however, require extremely bulky power supplies and modulation units because of high-voltage requirements. In comparison, cw transmitters of the same average power operate at lower voltages with less complex high-voltage design problems. The resnatron provides extremely high-power outputs, of the order of 30 kw, and can be crystal controlled; it was not seriously considered, however, because the average filament life of such a tube has been only about 150 hours. Moreover, the design features of a resnatron have been such that a vacuum must be maintained by continuous pumping.

The factor of bandwidth, B , is not an independent variable, since it determines not only the noise level but influences the signal threshold for a modulated system. From a propagation

point of view the signal bandwidth need only be wide enough to pass information on the tropospheric variations of the transmitted signal. Previous experience indicated that bandwidths of 10-100 cycles involve an extremely high degree of frequency stability (1 part in 10^8 to 1 part 10^9) both at the receiver and at the transmitter. Another method investigated was a system employing narrow-band sweeping techniques to follow the expected long-time frequency drifts of the transmitter and receiver oscillators. An analysis showed that the use of the sweeping technique does not permit detection of as weak a signal as does the narrow-band stabilized system with comparable detector characteristics. Pulse systems utilizing gating circuits in the receiver to improve noise thresholds offer considerable advantage in threshold detection, but require a high degree of gate synchronization, comparable to the frequency stabilization problem in the simpler cw narrow-band systems.

A survey of frequency stabilization potentialities of both crystal-controlled high-powered cw transmitters, and crystal-controlled receivers indicated that an over-all stability of the order of 100 to 200 cycles at 1000 Mc was feasible. Direct crystal control of the entire system was attractive because it eliminated complex sweep and gate circuitry in the receivers which would operate largely unattended except for periodic calibrations.

Attainment of low signal thresholds must be accompanied by provision of adequate signal generators capable of operating at low output levels, in order for practical measurements to be made.

By weighing all the practical problems of delivery dates, installation, operation, gain stability and maintenance aspects, together with the technical parameters, a system was designed incorporating extremely stable crystal-controlled transmitters with unusual freedom from undesired frequency modulation, and a narrow-band (500-cycle) crystal-controlled receiver recording system. Details of this equipment are described in the following sections of this report. Table I summarizes the transmission loss factors determining the margin of detectability finally achieved in the system, and Table II gives additional detailed data relative to the receiving system characteristics. Table III is a summary of the distances and bearings from the transmitter terminals to the various receiving sites.

Table I

TRANSMISSION LOSS FACTORS DETERMINING THE MARGIN OF DETECTABILITY
OF THE FINAL SYSTEM ADOPTED FOR CHEYENNE MOUNTAIN

| | <u>Frequency (Mc)</u> | | | | |
|----------------------------|-----------------------|------------|--------------|--------------|-------------|
| | <u>92</u> | <u>100</u> | <u>192.8</u> | <u>210.4</u> | <u>1046</u> |
| P_t (db) | 33.010 | 33.010 | 33.010 | 33.010 | 36.021 |
| L_t (db) | 0.089 | 0.104 | 0.304 | 0.185 | 0.215 |
| L_r (db) | 0.193 | 0.111 | 0.181 | 0.344 | 1.037 |
| G_t (db) | 9.25 | 9.98 | 10.40 | 10.60 | 26.00 |
| G_r (db) | 2.15 | 2.15 | 2.15 | 2.15 | 2.15 |
| L_f (db at 200 miles) | 110.478 | 110.472 | 115.759 | 116.313 | 114.843 |
| $10 \log_{10} f$ | 10 | 10 | 10 | 10 | 12 |
| $10 \log_{10} (kT)$ | -203.862 | -203.862 | -203.862 | -203.862 | -203.862 |
| $10 \log_{10} B$ | 30 | 30 | 30 | 30 | 28.45 |
| $10 \log_{10} \rho^*$ | 0 | 0 | 0 | 0 | 3 |
| P_m (db) | -163.862 | -163.862 | -163.862 | -163.862 | -160.412 |
| M (db) | 86.112 | 86.185 | 80.628 | 80.030 | 80.338 |

* This factor depends upon the receiver stability and can, in principle, be reduced considerably by averaging the detector output over a period of time for which the receiver may be considered to have stable gain and noise figure. The use of time constants greater than a few seconds, however, will have the effect of averaging out some of the fading of the received signal and thus in a loss of some of the information desired about the nature of the propagation.

Table II

RECEPTION CHARACTERISTICS - CHEYENNE MOUNTAIN TRANSMISSIONS

| <u>Location</u> | <u>Ground Eleva- tion Above Sea Level - ft.</u> | <u>Distance in Miles</u> | <u>Fre- quency Mc</u> | <u>Receiving Antenna Elevation Above Sea Level - ft</u> | <u>Antenna Type</u> | <u>Antenna Gain (Iso- tropic G_r)</u> | <u>Transmission Line Loss L_r</u> |
|------------------------|---|----------------------------------|-------------------------------|---|-------------------------|---|---|
| Kendrick, Colo. | 5260 | 49.4 | 92 | 5260 + 36.75 | Dipole | 2.15 | 0.46 |
| | | 49.3 | 100 | 5260 + 18.75 | " | " | 0.69 |
| | | 49.3 | 192.8 | 5260 + 17.50 | " | " | 1.03 |
| | | 49.4 | 210.4 | 5260 + 35.50 | " | " | 0.76 |
| | | 49.3 | 1046. | 5260 + 42.67 | " | " | 4.12 |
| Karval, Colo. | 5060 | 70.2 | 92 | 5060 + 36.75 | | 2.15 | 0.19 |
| | | | 100 | 5060 + 18.75 | | " | 0.12 |
| | | | 192.8 | 5060 + 17.50 | | " | 0.19 |
| | | | 210.4 | 5060 + 35.50 | | " | 0.35 |
| | | | 1046 | 5060 + 42.67 | | " | 1.03 |
| Haswell, Colo. | 4315 | 96.8 | 92 | 4315 + 36.75 | Dipole | 2.15 | 0.19 |
| | | 96.6 | 100 | 4315 + 18.75 | " | " | 0.12 |
| | | 96.6 | 192.8 | 4315 + 17.50 | " | " | 0.19 |
| | | 96.8 | 210.4 | 4315 + 35.50 | " | " | 0.35 |
| | | 96.6 | 1046 | 4315 + 42.67 | " | " | 1.03 |
| Garden City, Kansas | 2855 | 226.6 | 92 | 2855 + 36.75 | Dipole | 2.15 | 0.97 |
| | | 226.5 | 100 | 2855 + 18.75 | " | " | 0.74 |
| | | 226.5 | 192.8 | 2855 + 17.50 | " | " | 1.14 |
| | | 226.6 | 210.4 | 2855 + 35.50 | " | " | 1.71 |
| | | 226.5 | 1046 | 2855 + 42.67 | " | " | 1.87 |
| Anthony, Kansas | 1335 | 393.5 | 92 | 1335 + 39.00 | 57' Rhombic | 15.15 | 2.40 |
| | | | 92 | 1335 + 39.00 | 115' " | 15.95 | 2.8 |
| | | | 100 | 1335 + 39.00 | 57' " | 12.15 | 2.46 |
| | | | 100 | 1335 + 39.00 | 115' " | 15.55 | 2.84 |
| | | | 192.8 | 1335 + 39.00 | 115' " | 13.25 | 3.5 |
| | 1046 | 1335 + 30.00 | 10' Parabola | 26.15 | 3.75 | | |
| Fayetteville, Ark. | 1325 | 616.3 | 100 | 1325 + 38.00 | 120' Rhombic | 15.55 | 1.87 |

Table III

DISTANCE AND BEARING FROM TRANSMITTER

| <u>Receiver Site</u> | <u>Base Site</u> | <u>Summit Site</u> |
|----------------------|-------------------|--------------------|
| Kendrick | 49.4 - 106.375° | 49.3 - 105.569° |
| Karval | 70.2 - 97.627° | 70.2 - 97.059° |
| Haswell | 96.8 - 105.668° | 96.6 - 105.255° |
| Garden City | 226.6 - 105.424° | 226.5 - 105.247° |
| Anthony | 393.55 - 103.454° | 393.49 - 103.352° |
| Fayetteville | 616.3 - 103.67° | 616.3 - 103.67° |

LATITUDE AND LONGITUDE

Transmitter

| | |
|--------|---------------------|
| Base | 38.774° 104.862° |
| Summit | 38.764° 104.864° |

Receiver Sites

| | |
|--------------|---------------------|
| Kendrick | 38.569° 103.984° |
| Karval | 38.632° 103.572° |
| Haswell | 38.383° 103.141° |
| Garden City | 37.833° 100.858° |
| Anthony | 37.240° 97.898° |
| Fayetteville | 36.107° 94.107° |

III. SYSTEM DESCRIPTION

After studies on site selection and system design were completed, detailed plans for procedure were drawn up. Initially three general frequency ranges were selected: 100, 200 and 1000 Mc. The 1000-Mc region was selected to supply information in the 960-1600-Mc band allocated for aircraft communication and navigation. The 100 and 200-Mc systems offered a common basis of comparison for the general data being collected on a nation-wide recording program. This program, sponsored by the National Bureau of Standards, involves the recording of commercial FM and TV stations in locations having representative climatological conditions, usually under contracts with Universities or other qualified organizations. The data collected at Cheyenne Mountain under controlled conditions at both terminals, together with the data from the nation-wide recording program, would then provide propagation information for most types of locations and climate. Additional factors affecting the selection of these frequency ranges were the availability of surplus 100-Mc commercial FM transmitters and conventional tubes which could be used in amplifier-doubler stages at 200 Mc. A general description of the system is given under two major divisions as follows:

A. Site

A map of the area showing the location of transmitting and receiving facilities is shown in figure 2. Figures 3 and 4 are photographs of the two transmitting sites on Cheyenne Mountain showing the general installations. An idea of the relative heights of the transmitting terminals can be obtained by noting the appearance of Colorado Springs in the background of figures 3 and 4. Figure 5 shows the receiver installation at Kendrick, Colorado, and is typical of the four fixed sites where the terrain is essentially bare rolling hills departing from a smooth spherical surface by only a few hundred feet. As will be shown in a later section of our report, even such small irregularities are of major importance in connection with the propagation of 1000-Mc signals for which the wavelength is only about one foot. The distant portions of the path through south-central and south-eastern Kansas become progressively smoother but finally become much rougher at a distance of approximately 600 miles in the Boston Mountains of northwest Arkansas. Terrain profiles are shown in figure 6 for each 5-degree interval of true bearings from Cheyenne Mountain between 90 and 115 degrees. This terrain slopes from a ground elevation of approximately 6000 feet above sea level at the base of Cheyenne Mountain to approximately 1500 feet above sea level in western Arkansas.

The four fixed receiver sites were installed at distances from 49 to 227 miles. (See figures 2 and 6.) These were chosen to provide propagation measurements over paths that were (1) radio optical, (2) near the radio horizon, (3) a moderate distance beyond the horizon, and (4) far beyond the horizon. Since the nature of UHF propagation beyond the horizon is not well understood, a mobile receiver-recording system was designed and constructed for additional investigations of field strengths well beyond the horizon. This unit has been established at fixed points for several days and progressively moved to the more distant locations as indicated by the reception of recordable signals. A typical mobile installation is shown in figures 7 and 7a.

B. Equipment

The preliminary objectives of the Cheyenne Mountain experiments are to measure radio field strength produced near and far beyond the radio horizon with a carefully monitored transmission and recording system which is divided into four equipment classes: (a) Transmitting, (b) Receiving, (c) Recording, and (d) Calibrating. These are described generally as follows:

(a) Transmitting - The operating frequencies are 92, 100, 192.8, 210.4 and 1046.4748 Mc. The available continuous power output is 3 kw at 92 and 100 Mc and 4 kw at 192.8, 210.4, and 1046.4748 Mc. During propagation measurements the transmitted energy on each frequency is confined to a band less than 50 cycles wide. This in combination with narrow-band receivers insures the maximum "Margin of Detectability" for a given receiver and provides data at maximum distances. As pointed out in the description of system selection, the detectable signal in a given system is essentially a function of average power output, bandwidths, and threshold-detection factors. Reducing the receiver bandwidths or detection factors by 1/2 is effectively the same as increasing the average transmitter power output by a factor of two. As an example, if received signal power at some given distance were recorded on a regular commercial FM operation at 100 Mc where the receiver bandwidth is necessarily 150 kc and the effective radiated power of the transmitter 10 kw, the equivalent power for field-strength recording purposes could effectively be increased to 3000 kw by reducing the transmitter drift and incidental modulation to much less than 500 cycles and the effective noise bandwidth of the receiver to 500 cycles.

The frequency stability of each transmitter is capable of being maintained to within ± 200 cycles of the assigned carrier frequency. This insures that the transmitted signal power is measured within the $\pm 1/2$ db flat-top response of the receivers. The frequency-monitoring equipment for checking the transmitter frequencies utilizes a Hewlett-Packard frequency counter in conjunction with a General Radio Primary Frequency Standard.

All transmitting antennas have moderate power gains. Since the purpose of these studies was to observe propagation over air-to-ground paths under conditions similar to those of typical air-navigation systems, omni-directional transmitting and receiving antennas would have been most desirable. However, a mountain is not a typical airborne terminal because of other mountains to the rear and at either side. These mountains are excited by the RF fields of the transmitting antennas and reradiation occurs. In order to minimize this reradiation from the adjacent terrain and to approach the conditions expected for a typical air-navigation system some moderate directivity is desirable. A careful survey of the transmitting sites resulted in a choice of an over-all solid angle of radiation corresponding to ranges of 60 degrees in azimuth and 15 degrees in elevation. Figure 8 is a photograph of the transmitting antennas at the summit site. The VHF antennas at the base site are identical.

Modulation systems were provided in all transmitters to assist in carrier identification and to provide facilities for modulation studies.

(b) Receiving - The receiving equipment was designed to measure accurately the transmission loss on each of the five frequencies involved. It has several features to improve its stability characteristics and make it adaptable to a narrow-band recording system. General recording characteristics of all receivers are approximately the same, but the design and construction features of the VHF and UHF equipment differ widely because of frequency.

Both the VHF and UHF receiving equipment are frequency stabilized by multiplying the 100-kc output of a primary frequency standard to the appropriate oscillator injection-voltage frequencies. In locations where recordings are made on all frequencies, one common primary frequency standard is used for five receivers. The receiver circuits for feeding the data-recording equipment are essentially

the same for all receivers. The equipment installation and facilities in the mobile recording units are the same as those at the fixed recording sites.

(c) Recording - Received power is recorded at all locations on clock-driven charts, and at the more distant recording sites, where fading makes analysis of chart data impractical, on time-totalizing recorders. These time-totalizing recorders are equivalent to a battery of clocks, each one recording the total time that a certain pre-set signal level is exceeded. Each clock is activated by the receiver when the appropriate pre-set signal level is crossed. Readings of the clocks are periodically recorded by an automatic camera system.

(d) Calibrating - The calibration of receivers and measurement of the available signal power from the system is based on a comparison between that available from the receiving antenna transmission line and that available from the output of a calibrated signal generator with the same impedance (50 ohms). All signal generators used at various locations are related to a standard and to transmitter power indication devices.

IV. SYSTEM COMPONENTS

The system for collecting propagation data may be divided into three equipment groups. These are: (A) Transmission, (B) Reception, and (C) Data Recording. These groups are further divided according to frequency range and individual components; they are discussed in detail appropriate to their importance or unusual features as follows:

A. Transmission

The transmission system includes all of the basic components as outlined in block diagram form on figure 9.

(a) UHF Transmitter - 1046 Mc. This transmitter was built by Varian Associates of San Carlos, California, for the National Bureau of Standards. Its installation in the summit building on Cheyenne Mountain is shown in figure 10. It was designed to meet the rigid specifications of the narrow-band, continuous-wave radio propagation system for Cheyenne Mountain. This transmitter meets the essential system requirements of radiating a high-power, essentially monochromatic, stable, continuously monitored radio-frequency signal at 1046.4748 Mc.

It is described in more detail than the VHF units because the transmitter is unique in having the highest continuous power output of any 1000 Mc transmitter in the country. It consists of four major components. They are: (1) the crystal driver unit, (2) the klystron power amplifier, (3) the direct current power supplies, and (4) the antenna systems. The driver unit and the klystron amplifier installation may be seen in figure 10.

(1) The Crystal Driver Unit - The basic requirements for a driver unit for this type of transmitter were very exacting and necessitated the employment of a number of rather unique design features. The first of these requirements was that an extremely stable basic crystal source be chosen so that multiplication of the output frequency of the crystal standard 10,368 times could result in an essentially monochromatic output with a long-term variation of less than 250 cycles at 1046 Mc. A General Radio primary type 1100 AP frequency standard was selected to meet these requirements. For reasons of technical simplicity in the receivers, the output frequency desired was not an exact multiple of 100 kc. A crystal unit approximately 1 percent higher was used. The General Radio Company cooperated with the Central Radio Propagation Laboratory in this problem by designing this special crystal at 100.93315 kc and performed appropriate tests to verify adequate performance. Long-term experience over the past six months has shown that the actual total variation between two General Radio Standards is less than 125 cycles at the final 1046-Mc frequency. (The second standard is used as a crystal unit for the local oscillator multiplier chain in the receiver.)

The second requirement specified that the driver output at 1046 Mc should be free of all types of modulation and noise, and have a constant power output. To accomplish these results, considerable effort was spent in the design of this unit. The plates and filaments of all tubes are operated on well-filtered, DC-regulated supplies, which are in turn supplied by AC regulators. To reduce spurious outputs and unwanted modulation components, the stages are arranged as follows: All of the low and medium frequency multiplier stages consist of two tubes with the grids connected in push-pull and plates connected in parallel (for the doublers), and both grids and plates in push-pull for the triplers. All of the input and output circuits and high Q, double

tuned and slightly undercoupled. The radio frequency drive on all stages is sufficient so that the transconductance of a tube can drop to 50 percent of its normal value without affecting the over-all output of the transmitter. In practice it has been possible to operate at full output for a period of several weeks with the tubes in two of the stages having transconductances of less than 20 percent of normal values. The high-frequency multiplier stages are grounded-grid, coaxial-cavity type multipliers. In these stages, as in the lower frequency strip, all of the above-described precautionary measures against unwanted modulation components are employed with one single exception; these stages consist of a single tube. The arrangement of the driver unit is shown in the block diagram of figure 9.

(2) The Klystron Power Amplifier - The final amplifier consists of a 4-kw output, three-cavity, klystron tube and associated components. This type of tube in itself presents a unique solution to the high-powered problem in this frequency range. The tube is a low-efficiency device, generally of the order of 20 to 25 percent, but this disadvantage is greatly offset by the extremely high gain of the tube in this circuit (400). The arrangement of the tube elements is shown in figure 11. Basically, the tube operates as follows: The filament is heated from a 6-volt supply and requires 50 amperes for normal operation. The difference in potential between the cathode and filament is 2200 volts, which produces by electron bombardment the heating of the tantalum cathode, the primary source of the electron beam. A further difference in potential of 11,000 volts exists between the cathode and the body of the tube, which in turn produces the high-velocity electron stream moving through the drift space and the cavities. These electrons are absorbed by the catcher or bucket, causing it to heat up. This heat is removed by a large-capacity water cooling system. The operation of the tube is similar to that of low-powered klystron tube types, except that the electron beam is magnetically confined to the correct path by use of three focusing coils around the cavities.

A number of rather interesting circuits have been employed to maintain constant power output from the tube under operating conditions. For example, since the electron emitter source is operated as a temperature-limited device, it is necessary to maintain the input power

to the filament-cathode constant. This is accomplished in the following manner. The cathode supply is regulated to keep the cathode temperature as nearly constant as possible in order to maintain the temperature-limited beam current at a constant value. This circuit uses a saturable reactor which has one primary and two secondary windings. The primary is in series with the transformer which supplies the klystron with its filament power. The basic function of the reactor is to control the impedance of this primary winding and thus control the filament power. The filament is operated temperature-limited so that a decrease in reactor primary impedance will increase the filament power and so increase the cathode current and temperature. One of the secondary windings is a "bias" coil. The bias current is made up of a constant current plus a compensating current which decreases when the line voltage increases. The constant current is about four times that of the compensating current and sets the level of saturation of the reactor and therefore the level of the filament power. The second of the reactor secondary coils carries the cathode current. The current in this coil has an effect opposite to the current in the "bias" coil. The reactor is designed so that an increase in the cathode current will increase the impedance of the reactor coil primary and so decrease the filament power. This prevents the cathode current from becoming excessive due to the "back heating effects." The saturable reactor prevents this "running away" because an increase in cathode current causes a decrease in the filament power to compensate for the increase in back heating. However, this effect is not large enough to keep the cathode power constant with changes in line voltage. If only the cathode coil of the reactor were sensitive to line voltage changes, an increase in line voltage would cause an increase in cathode voltage and a small increase in current would result. Therefore, the bias current is also made sensitive to line voltage in such a way that an increase in line voltage causes a decrease in cathode current sufficient to keep the cathode power almost constant. This is accomplished by making the compensating portion of the bias current decrease with an increase in line voltage. This, in turn, reduces the total bias current and therefore the filament power and the cathode power, thus giving the over-all effect.

Approximately 12 kw of heat are dissipated in the klystron "bucket" under normal operating conditions. Cooling water is circulated through the klystron catcher bucket and the tube body, using a pump for circulation and an external radiator for cooling. The water for the catcher bucket is

metered with a flowmeter and a thermometer. These are both connected electrically into the beam voltage supply, so that a failure of water flow or excessive temperatures will automatically remove the beam voltage. The body water flow is determined by two pressure gauges with associated interlock circuits so that a failure of body water flow will turn off the klystron filament, cathode and beam voltages.

The last major unit of the klystron unit is the regulated Focus Coil Supply. This supply furnishes current for the three focus coils. The current in the top and center coils flows in the same direction but the current in the bottom coil flows in the opposite direction. The purpose of the bottom coil is to counteract the effects of the two top coils on the formation of the electron stream at the cathode.

Some of the electrons in the beam are attracted to the cavity structure resulting in a small "body" current. This current is dependent primarily upon the focus coil currents, but is also influenced by the degree of RF modulation or "bunching" in the electron beam. The power gain and output of the klystron are also a function of the focus conditions of the beam. In practical operation, the currents in the focus coils are adjusted to give maximum output power while keeping the body current minimized.

(3) The Beam Power Supply -- The power supply consists of three basic units: -1- the high voltage rectifier unit and associated AC control circuits, -2- the DC regulator unit, and -3- the control panel. The power unit operates on three-phase 208 or 230 volts AC and is capable of supplying 14,000 volts at about 2.0 amperes. The circuits of the high-voltage rectifier and the stabilization equipment are shown in figures 12 and 13, respectively.

The operation of the power supply as a unit can best be described in conjunction with the description of the regulator unit. The regulator unit consists of a two-stage DC amplifier, an adjustable reference voltage source, regulated power supplies and the high-voltage divider. Referring to the block diagram on figure 9, it can be seen that the high-voltage divider balances the high negative output voltage against the positive reference voltage. The voltage unbalance signal from the divider is fed to the DC amplifier and after

amplification appears as a large controlling voltage at the grids of the gate tubes. This voltage on the grids of the gate tubes alters their conduction in such a direction as to minimize the unbalance signal at the input of the DC amplifier. Thus, within the limits of the amplifier and the gate-tube range, the output voltage is quite closely proportional to the reference voltage.

It can be noted in the block diagram that no LC filters are used but filtering and regulation are entirely dependent upon electronic circuits. The basis for this exact regulation is the use of five Weston standard cells as a reference voltage source. In this way the two standard reference supplies (for the DC amplifier and tubes in the high-voltage reference supply) are maintained within a few mv of rated voltage. As an example, the high-voltage reference supply will show a change of less than 5 volts at 4850 volts with the input line voltage changing from 212 to 248 volts.

The high-voltage rectifier unit consists of two full-wave three-phase systems connected in series, so arranged as to produce the equivalent of a 12-phase system. The gate tubes consist of four 3X2500F3 Eimac tubes in parallel. The entire rectifier system can be controlled remotely from the transmitter control panel, thus greatly simplifying transmitter operation.

(4) The Antenna and Power Measuring System - The antenna system consists of two moderate gain antennas and associated feed systems. The first, for horizontal polarization only, is a slot-fed, tapered array, guided by a divided horn. With this arrangement side lobes are attenuated to below the 20-db level while the vertical beam is maintained at 15 degrees, and the horizontal at 60 degrees. The second is a parabolic section illuminated by a horn, with the horn feed so arranged that either horizontal or vertical polarization can be used. The patterns and side-lobe conditions are essentially the same in each polarization as for the first antenna. Both antennas are tuned at the feed points by double stub tuners, thus maintaining a low SWR in the 3-1/8 inch coax line and allowing the maximum power transfer out of the klystron.

Absolute power of the transmitter is measured by a watt-meter which is essentially a coaxial water load with provision made for measuring the temperature rise of the water flowing through the load. The calorimetric load is

made from standard 3-1/8 inch line by a gradual transition from air-to-water around the center conductor. The RF power heats and is absorbed in the water as it flows through the load. The input and output water temperatures are measured and the power calculated.

In addition, a continuous monitor is provided in the form of a Bethe-hole directional coupler, crystal detector, tuning stub, and power meter. This meter reads the forward power flowing from the klystron towards the load. When the load is well matched, the meter indicates the power output of the transmitter directly.

(b) VHF Transmitters - 92, 100, 192.8, and 210.4 Mc (see figure 14). The 92-Mc transmitter installed on the mountain at the base site (elevation 7700 feet above sea level) and the 100-Mc transmitter installed at the summit site (elevation 8800 feet above sea level) are conventional commercial 3-kw FM-broadcast transmitters with provision for the use of a high-stability crystal-controlled frequency source and primary voltage regulation.

The 192.8-Mc transmitter at the summit site and the 210.4-Mc transmitter at the base site are adaptations of conventional commercial FM transmitter driver circuits with the addition of final power amplifier doublers. These are interesting in that conventional 3X2500 A3 tetrodes, although not normally employed at such high frequencies, were used for economic reasons and to simplify construction. These have given consistently reliable performance with a tube-life averaging well over 4000 hours. The frequency control of these transmitters also has provisions for more stable crystal control.

The antennas for all frequencies from 92 to 210.4 are corner reflector types driven by half-wave dipoles and matched to 50-ohm 3-1/2-inch coaxial transmission line. These antennas have gains of approximately 10 db relative to an isotropic radiator and directivity patterns such that only a small amount of the radiated energy strikes the mountain behind and below them. The power output of the transmitters is continuously monitored with a wattmeter periodically calibrated against a calorimeter load.

In addition to the VHF transmitters described above a 1-kw commercial-type FM transmitter operating on 100 Mc has been installed in a house-type trailer. This mobile transmitting system will be used to make additional height-gain

studies by transmitting from the base of Cheyenne Mountain at approximately 6000 feet above sea level and from Pike's Peak at an elevation of 14,250 feet. The power output, voltage regulating, and frequency-control systems of this transmitter are essentially the same as the others. The frequency of 100 Mc was chosen in order to take advantage of existing receivers.

B. Receiving

Receivers are also divided into two groups, UHF and VHF. A block diagram of the UHF receivers is shown in figure 15. A block diagram of the VHF receivers showing general construction and frequency relations is shown in figure 16.

(a) UHF Receivers - 1046 Mc. The 1046-Mc receiver was designed and constructed by the Polytechnic Research and Development Co. and design considerations were to obtain narrow-band, extreme-frequency stability, and high-gain stability. The receiver has a signal bandwidth of 500 cycles between points one db down from the maximum response. A noise figure of approximately 12 db above KTB noise has been attained in this receiver. This narrow bandwidth and low noise figure yield a sensitivity, P_m , of approximately -160 db (0.07 microvolts across the 50-ohm receiver terminals). The receiver is of the double super-heterodyne type with the local oscillators crystal-controlled by multiplier chains operating from a 100-kc General Radio type 1100-AP primary frequency standard. The output circuits of this receiver were designed specifically to operate with 1-5 ma Esterline-Angus recorders and 0-10 volts high-impedance time-totalizing equipment. The output response of this receiver is approximately linear in both voltage and current with logarithmic input signal power. The dynamic ranges available are 0-20 db, 0-40 db, 0-60 db. The receiver consists of a number of integral units which may be removed separately. The first of these major units is a preselector of the coaxial-cavity type. The selectivity of this tunable coaxial cavity is such that signals 25 Mc either side of resonance are attenuated by 30 db. This unit has an insertion loss of approximately 1 db at the 1046-Mc operating frequency. The signal out of the preselector is fed to the next component of the system, which is a coaxially-mounted crystal mixer of conventional design. This third component of the receiver is a crystal multiplier chain operating from the basic 100-kc frequency standard and consists of two integral strips. The first of these strips operates directly from the 100-kc crystal standard and consists of a series of tuned multiplier stages which produces an output signal at

9.6 Mc. This output serves both as a local oscillator for the second mixer and drives the second high-frequency multiplier strip. This latter multiplier strip consists of several tuned multiplier stages of which the last tripler stage is an RCA pencil triode mounted in a coaxial cavity. This last stage provides a local oscillator power for the crystal mixer at 1036.8 Mc. The fourth component of the receiver is a 9.675 Mc IF strip. This strip consists of several singly-tuned stages of relatively conventional design. The last stage of this strip is of typical cathode follower design providing a 50-ohm BNC coaxial cable termination. The output of this strip is fed into a push-button attenuator with five attenuation settings: 0, 3, 5, 20, and 40 db. The 9.675 Mc output from this strip is fed to the second mixer where it is heterodyned with the 9.675-Mc local oscillator previously mentioned in the multiplier chain. The 75-kc IF frequency from this second mixer is fed into the second and final IF strip. The narrow band of 500 cycles is attained in this final strip. Carefully designed double-tuned stages are used to obtain a flat-top response curve with a high skirt selectivity. The detector circuit is built into the last stage of 75-kc IF amplifier. An automatic volume control circuit designed to provide a linear output vs decibel ratio of input signal is included in this strip. Deviation of the desired signal within the narrow bandwidth can be monitored by a high "q" parallel tuned circuit, adjustable over a range of plus or minus 500 cycles from the 75-kc center frequency. The last component of the receiver consists of two electronically regulated plate voltage supplies and a filament voltage supply. The IF amplifiers are operated from one plate voltage supply, and the multipliers and frequency deviation circuits are operated from the other. All filaments in the entire system are operated from the regulated DC voltage supply.

(b) VHF Receivers - 92, 100, 192.8 and 210.4 Mc. These receivers have been constructed by the Polarad Electronics Corporation of Brooklyn, New York. Special features are utilized to improve gain and frequency stability, and to obtain a very narrow recording channel bandwidth. They are of a triple superheterodyne type, the frequency for oscillator injection voltages being controlled by the same 100-kc primary frequency standard as employed for the 1046-Mc receiver. The receivers are identical for each of the frequencies from 92 to 210.4 Mc with the exception of the preselector preamplifier and the first crystal oscillator multiplier circuits. A detailed description of the oscillator frequencies, and of the frequency multiplier

system is shown in figure 16. The transmitter frequencies were chosen for adequate separation of all fundamental and harmonic frequencies, and so that suitable receiver-oscillator frequency multiplication factors could be employed. The over-all effective narrow bandwidth of approximately 1 kc is obtained in the 200-kc third intermediate frequency amplifier which has associated with it a discriminator for determining that the transmitter and receiver are tuned to the same frequency. The 200-kc final IF frequency was selected so the second harmonic of the primary frequency standard which is adjusted to 100 kc by comparing it with WWV, may be used to calibrate the receiver discriminator circuit.

C. Recording

The same type of data-recording equipment is used with all receivers and consists of an Esterline-Angus clock-driven chart recorder and a 10-channel totalizing clock operated by the receiver AVC voltage and recorded by an automatic camera. The totalizing recorder is designed to operate with a receiver DC output voltage over a 0 to -10-volt range. This voltage is an approximately logarithmic function of the radio frequency input voltage to the receiver. Each channel consists of a stabilized DC amplifier driving a bistable multivibrator which actuates a relay. The relay in turn operates a motor, revolution counter, and pilot light. The sequence of operation (see circuit diagram in figure 17) for each channel is as follows. Negative input DC voltage from a receiver is applied to the grid of the amplifier V_1 , with a compensating negative bias applied to the grid of the upper tube V_2 . When the magnitude of the input voltage exceeds the negative bias applied to the upper tube, the grid of the left multivibrator tube V_3 is driven positive in excess of 60 volts. The multivibrator is normally operated with V_3 cutoff and V_4 conducting, holding the relay contact open. When V_3 is rendered conducting by the positive input from the DC amplifier, V_4 is cutoff, releasing the relay and operating the motor, pilot light and counter. V_3 is periodically cutoff by negative pulses (at a rate of 1000 per second) from the blocking oscillator. The presence of these pulses reduces the difference between the voltages required to activate and deactivate the multivibrator. The resistor R_1 allows an adjustment of each channel to a desired pre-set level at which all input signals equal to or in excess of that level will operate the ten counters.

A typical fixed-site recording installation is shown in block diagram form in figure 18.

Figure 19 shows a typical receiver totalizing recorder calibration in terms of receiver input voltage from a standard signal

generator for a period of one week. Successive calibrations are shown to give an idea of system stability. Figure 20 is a photograph of the inside equipment in a mobile recording trailer showing rack-mounted data recording equipment and receivers.

D. Calibration

The value of received signal power at the receiver input terminals is determined by comparing the signal level with an equivalent level from a calibrated signal source. The signal sources used are divided into two classes, VHF and UHF. These are discussed separately as follows:

(a) UHF - 1046 Mc. The narrow bandwidth, extreme frequency stability, and high sensitivity of the 1046-Mc UHF receivers make it necessary to employ special signal generators for calibration purposes. These signal generators consist of three major components. The first of these is a series of frequency multipliers, similar to those of the local oscillator of the receivers, controlled by a Bliley Type BCS frequency standard of 100.93315 kc. This basic frequency is multiplied 10,368 times to give the transmitter frequency of 1046.4748 Mc. The power output of this multiplier chain is monitored by a UHF Hewlett-Packard type voltage probe and indicates the level on a meter on the front of the panel. The second component of the signal generator is a carefully designed wave-guide-below-cut-off type of attenuator. When the power output of the multiplier system is calibrated to the normal reference level, the output of the attenuator can be varied from zero to -140 dbm with an accuracy of plus or minus 0.5 db. The panel dial of the attenuator is calibrated in both db above one milliwatt and in microvolts. The attenuator has an output impedance of 50 ohms with a VSWR of less than 1.2. The power supplies are the last major component of the signal generator and are similar to those used in the receiver.

(b) VHF - 92 through 210.4 Mc. The signal-generator design problems in this frequency range are less stringent than in the higher frequency UHF band, and crystal control, though highly desirable, has not been found to be absolutely essential. Conventional signal generators using calibrated wave-guide-below-cut-off type of attenuators have proven marginally satisfactory when used with external voltage regulation and under stabilized temperature and vibration conditions. Frequency adjustments are accomplished by adjusting the signal generator frequency until the signal

source frequency is at the center frequency of the final IF band as indicated by the receiver frequency meter. Since this meter is compared to a primary frequency standard at 200 kc this method of setting the frequency of the signal generator to the frequency of the transmitter is very accurate. Calibrations of the signal generators are made by the High Frequency Standards Section of Division 14 of the National Bureau of Standards. These are maintained by continuous checks with bolometer bridges and a cross comparison between generators. A system of comparing RF voltages with accurately measured 60-cycle voltages by means of selected, essentially flat frequency response, crystal diodes has also been successful.

V. SYSTEM OPERATION

Propagation data at Cheyenne Mountain are collected on a continuous twenty-four-hour-per-day basis. This schedule is limited only by loss of time due to regular maintenance or equipment failures. Less than 60 percent of this goal has been realized to date because of slow equipment deliveries, new equipment faults, the problems of perfecting system operation, and the training of operating personnel.

As of March, 1952, however, all transmitters were operating on a continuous schedule. The fixed sites at distances of 49.3, 70.2, 96.6, and 226.5 miles are visited and calibrated at least once each day. The mobile sites have been operated for relatively limited periods at several locations. It is not planned to make continuous measurements at long distances but to take periodic samples of data during typical seasonal climatological conditions. Some special recordings planned for the near future include samples of data at distances equivalent to the fixed sites over several dissimilar paths and recordings at many additional locations over line-of-sight paths.

VI. SYSTEM RESULTS

Field-strength recordings have been made on all frequencies at various distances from the transmitters. Recordable signals have been received on 92, 100, 192.8, and 1046 Mc as far as Anthony, Kansas, a distance of 393.5 miles, and on 100 Mc at Fayetteville, Arkansas, a distance of 616.3 miles. Recordings are now being made at each of the four fixed receiving sites shown in figure 2 on a regular basis in order to obtain measurements over an extended period of time for the purpose of studying the effects of diurnal and seasonal factors on the transmission loss (received field strength) as a function of distance, frequency, and antenna heights.

Figure 21 shows sample fast-speed recordings of the field strengths received on 92 and 1046 Mc at a distance of 393.5 miles. Calibration scales are shown in terms of "transmission loss"^{3/}, microvolts input to the receiver and, for the 1046-Mc recordings, signal power available from the receiver transmission line in db below a milliwatt. Transmission loss^{3/} is considered to be the ratio of the power radiated from the transmitting antenna to the resulting signal power which would be available from the receiving antenna if it had no ohmic losses. Expressed in db, the measured transmission loss of a system may be written:

$$L_m = (P_t - L_t) - (P_a + L_r) = P_t - P_a - (L_t + L_r) \quad (5)$$

where P_t , L_t , and L_r were defined earlier and P_a = measured signal power available at the terminals of the receiver transmission line expressed in db above one watt.

Reporting measurements in terms of transmission loss avoids the assumption that a plane-wave front is received by the receiving antenna and thus that the full free-space antenna gains will be realized; this may not be the case if the received fields arrive from a number of directions after being scattered in the transmission medium.

The short spikes of high signal intensity which appear on the 92-Mc recordings of figure 21 are believed to be the result of reflections of the signal from ionized meteor trails as has previously been reported in connection with FM broadcast reception^{4/} and which have been the subject of independent research^{5,6/}. These spikes are not evident in the 1046-Mc recordings. These sample recordings, having been taken with a short time constant and an accelerated chart speed, give a representative picture of the relative magnitude and rapidity of fading at this distance on these two frequencies. It may be seen that, while the amplitude of fading on the two frequencies is roughly the same, the frequency of fading on 1046 Mc is about 10 times that on 92 Mc, i.e., roughly proportional to the frequency.

Results of the measurements on all frequencies of the Cheyenne Mountain transmissions in terms of transmission loss for the period January 20, 1952 to April 1, 1952 are shown in figure 22. These are medians of the hourly median recorded field strengths shown for the periods of recording given in Appendix I.

In figure 23 the results have been plotted in terms of transmission attenuation relative to free space as determined by use of the following expression:

$$A = L_m - L_f = L_m - 20 \log_{10} (4\pi d/\lambda) + G_t + G_r \quad (6)$$

Results expressed in terms of attenuation relative to free space assume that the gains of the antennas as determined for reception of plane waves in free space are realized. Also shown for comparison on figure 24 are the results of the Federal Communications Commission Ad Hoc Committee for 98 Mc with a transmitting antenna height, h_t , of 2000 feet and a receiving antenna height, h_r , of 30 feet as well as the results of Fine and Higgins for the frequency range 288-700 Mc.

It may be seen from this figure that there are two distinct regions, the near region where the field strength falls off rapidly with distance and the far region where the field strength decreases much more slowly with distance. The rapid decrease in the very near region is generally in accordance with what would be expected using conventional diffraction theory. However, in the very far region the measured transmission losses are far less than those expected with conventional theory. A plausible explanation of these low transmission losses in the very far region has been given by Dr. Joseph Feinstein of the National Bureau of Standards in his recent application of the partial reflection theory to the tropospheric propagation problem. This partial reflection theory is an extension of the results obtained for a slowly varying medium by Dr. H. Bremmer of the Philips Laboratories at Eindhoven, Holland.

Curves of field strength vs distance, calculated in accordance with the authors' interpretation of the partial reflection theory, are shown in figure 25 together with the same measured data appearing in the previous figure. The agreement between measurement and the partial reflection theory in the far region is remarkable. Figure 26 shows the geometry involved in the partial tropospheric reflection theory for the path between Cheyenne Mountain and Anthony, Kansas. The terrain has been plotted assuming an effective earth's radius 1.231 times the actual radius to allow for average air refraction expected in Colorado during the month of February. The four ray paths shown are rays which have the same angle of incidence and reflection at an assumed layer in the troposphere concentric with the earth and are tangent to the earth's surface at the horizon points as seen from the transmitting and receiving antennas. It may be seen that, at a distance of 400 miles, these assumed reflection points occur at heights from about 15,000 to 35,000 feet above the earth's surface.

The existence of four separate ray paths is more clearly illustrated in figure 27 where a plane earth representation of the earth and a reflecting layer is shown. In the upper portion of the figure the concept of having one tropospheric reflecting point for both the direct and ground-reflected waves is illustrated. However, in this representation, Snell's law, requiring equal angles of incidence and reflection at both the ground and the reflecting layer, is not satisfied for the ray paths between the transmitting and receiving antenna. The lower portion of the diagram illustrates the four ray paths determined by satisfying Snell's law at each reflecting surface: (1) r_1 , the direct ray from the transmitting to the receiving antenna, via the reflecting layer, (2) r_2 , the direct wave from the transmitting antenna first striking the reflecting layer and then being reflected at the ground near the receiving antenna, (3) r_3 , the ground-reflected ray from the transmitting antenna arriving via the layer directly to the receiving antenna and (4) r_4 , the ray which is reflected at the ground on each side of the reflecting layer.

The existence of a number of separate ray paths also provides an explanation for the observed statistical Rayleigh distribution of instantaneous field strengths for relatively short periods of time as is illustrated in figure 28 for measurements taken at Anthony, Kansas, and Fayetteville, Arkansas.

The distributions of hourly median signal levels for the 100 and 1046-Mc transmissions at the various distances are shown on figure 29, and for the 92, 192.8 and 210.4-Mc transmission on figure 30. The total number of hours of data included in these samples is shown on each distribution curve. It should be noted that the variances of these distributions are generally smaller at the distances within and near the radio horizon (70.2 miles and less) and in the very distant region, 226 miles and beyond, than they are at the intermediate distance of 96.6 miles. An explanation for this result may lie in the manner in which the field strength varies with time of day at the various distances as shown in figures 31 and 32. Over the shorter paths very little diurnal variation of signal strength is observed; however, at Haswell, Colorado (96.6 miles), there is a definite increase in field strength during the nighttime hours from that observed at midday. And then at Garden City, Kansas (226.5 miles), and Anthony, Kansas (393.5 miles), this characteristic diurnal variation is again not observed.

Figure 33 shows sample recordings of the 100-Mc Cheyenne Mountain transmissions made at Fayetteville, Arkansas. The

upper record is a sample of recordings made with the recorder tape running 3 inches per hour and with a 20-second averaging time constant in the recording circuit. The transmitter carrier was turned off on the hour for ten minutes and these periods are strikingly clear of noise or of interfering signals. The lower chart was made with a recorder tape speed of 3 inches per minute. This record is very similar to the sample recordings shown in figure 21 for 92-Mc transmissions at a distance of 393.5 miles, particularly with regard to the period and extent of fading of the background signal. Of particular note is the considerably more frequent appearance of the previously mentioned short-duration spikes of high signal strength, associated with meteoric ionization, riding on top of the weaker background signal.

The possibility that partial tropospheric reflections occur at such great heights in the troposphere (greater than 15,000 feet) provides an explanation for the lack of a pronounced diurnal trend at these great distances, since variations in the gradient of refractive index with height would not be expected to have large variations at these great heights as compared to the relatively more turbulent portion of the atmosphere very near to the earth's surface. The refractive-index gradient at the effective point of partial reflection is one of the important factors determining the strength of the received field strength under the partial reflection theory.

Figure 34 shows the average refractive-index gradient as a function of height for the Cheyenne Mountain path in the months of February and August as determined from the 1945 Weather Bureau Ratner Report.^{10/} The February values shown on this figure were used in calculating the curves on figure 25. The climatic variation of the gradient of refractive index up to large heights above the earth's surface is shown in figure 35. San Juan in July was chosen as an example of a warm, humid climate; Washington, D.C. in October as a temperate or median climate; and Fairbanks, Alaska, in February as a dry, cold climate.

In order to investigate the extent to which the received field strengths fade together on two spaced antennas, simultaneous recordings were made on 92 Mc at Anthony, Kansas, using two rhombic antennas. The lengths of the antennas were 5.31 and 10.75 wavelengths on a side, and the two antennas were displaced 50 feet in a direction normal to the propagation path. Sample results are shown in figure 36. With 50-foot antenna separations, it may be seen by inspection that the background signals from the two antennas are very closely correlated and

fade together. Also it may be noted that the transmission loss is less on the smaller rhombic antenna by approximately the difference in gain. These observations indicate that the wave front is essentially coherent and plane over the area taken up by the two antennas. Generally, the spikes of high signal strength of meteoric origin are more prominent on the shorter rhombic antenna which has a broader antenna pattern and consequently less discrimination against signals arriving from angles of incidence much above the low angles for which the rhombic antennas were designed.

Figure 37 shows sample simultaneous recordings taken on 92 Mc and 100 Mc using the two rhombic antennas. In this case the received signal strengths appear entirely uncorrelated except for the times at which the meteoric signals occur. Under these conditions, not only is the frequency different but also the transmitter heights are widely different.

VII. A FORMULA FOR THE TRANSMISSION LOSS OF SPACE WAVES PROPAGATED OVER IRREGULAR TERRAIN

In order to provide methods of extrapolating the Cheyenne Mountain results to other transmission paths for which the terrain and the atmosphere are different, considerable time and effort were expended in the development of formulas suitable for calculation of the transmission loss expected under a wide variety of conditions. This section of this report outlines the results of one phase of this study, i.e., a formula for transmission loss calculations at points within the radio line of sight.

A space wave^{11/} is that part of the ground wave which consists of the direct and ground-reflected waves, i.e., it does not include the surface wave. The ground wave is predominantly a space wave whenever the transmitting and receiving antennas are both elevated by more than a wavelength above the ground. Since the surface-wave intensity is much less with horizontal than with vertical polarization, the ground wave is always less contaminated with a surface-wave component in the former case. The data presented in this paper were all obtained with horizontally polarized radio waves.

The present discussion is concerned with space waves only within the "line of sight" of the higher of the two antennas comprising the transmission system. For the purposes of this discussion "line of sight" is defined in a particular way and the maximum distance from the highest antenna at which the methods herein apply corresponds to the "space wave horizon"

of this antenna as defined in figure 38. The detailed methods of arriving at the precise location of this "space wave horizon" will be developed later. At this point it may be briefly described as the maximum distance at which the terrain would be illuminated by a source of radiation at the location of the higher of the two antennas comprising the transmission system.

Our development of a transmission-loss formula is based upon the determination of a smooth curved surface (either concave or convex) which approximates that part of the actual terrain which is effective in the ground-reflection process, and the subsequent use of well-known methods of attenuation calculation applicable to such smooth curved surfaces. For example, methods have been outlined in a paper by the author^{12/} for ground-wave calculations over a smooth spherical surface. Expressed in terms of transmission loss, this formula may be written:

$$L_c = 36.58 + 20 \log_{10} d + 20 \log_{10} f_{mc} - 10 \log_{10} \left[g_{1d} g_{2d} + D^2 |R|^2 \left(\frac{d}{d_1 + d_2} \right)^2 g_{1r} g_{2r} + 2D |R| \left(\frac{d}{d_1 + d_2} \right) \sqrt{g_{1d} g_{2d} g_{1r} g_{2r}} \cos (\theta + c) \right] \quad (7)$$

The geometry involved is illustrated on figure 39; the antenna power gains, g_{1d} , g_{2d} , g_{1r} , and g_{2r} are also illustrated. In the above formula the distances are expressed in statute miles.

$$\theta = \frac{2\pi}{\lambda} (d_1 + d_2 - d) \approx \frac{4\pi h_1' h_2'}{\lambda d} \quad (8)$$

$|R|e^{iC}$ = plane wave ground-reflection coefficient

$$D = \left[1 + \frac{2 d_1 d_2}{k_t a d \sin \psi} \left(1 + \frac{k_t \sin^2 \psi}{k_t'} \right) \right]^{-1/2} \quad (9)$$

The above divergence factor, D , applies to convex surfaces for which k_t is positive and becomes a convergence factor for concave surfaces for which k_t is negative. This equation for D is, to a high degree of approximation, the same as that given by Riblet and Barker^{13/} for the case where the principal radii of curvature at the bounce point are taken to be parallel and normal, respectively, to the great circle plane through the

transmitting and receiving antenna locations. The radius of curvature of the surface in this great circle plane is $k_t a$ and normal to this plane $k'_t a$. At points near the horizon, (7) will not apply since D_t approaches zero for convex surfaces and in this case it is necessary to interpolate between (7), which is applicable at short distances, and a diffraction formula applicable at large distances; this method of interpolation is fully described in the reference cited^{12/}.

A solution may now be obtained by finding the spherical surface (either convex or concave) which most nearly approximates the actual terrain. A simplification in determining this spherical surface may be made when we note that the only part of it of importance lies near the great-circle arc of this sphere which passes from the base of the transmitting antenna to the base of the receiving antenna. The physical basis for this latter simplification may be established by locating the first Fresnel zone on the reflecting surface. This first Fresnel zone will be found to be a long narrow ellipse with its major axis lying along the great-circle arc, and we know that the part of the terrain of greatest importance in determining the intensity of the ground-reflected wave is that part lying within this first Fresnel zone. An example in the visual spectrum of this phenomenon of reflection is furnished by the reflection of the moon in the surface of a lake. When the surface of the lake is perfectly smooth, a perfect image of the moon appears on the surface at the location corresponding to the points of reflection of the ground-reflected rays of geometrical optics. Since the moon is not a point source, its image in the surface does not occur at a point but extends over a small area. When the surface of the lake is rough, however, the image of the moon becomes a long narrow path of light extending from a point on the surface near the observer to a point far beyond the location of the smooth surface image. The important thing to notice in connection with this well-known visual phenomenon is the fact that the roughness of the reflecting surface does not widen the smooth surface image appreciably but does lengthen it by a very large amount. Thus we may expect to obtain a very good approximation to irregular terrain space-wave transmission loss calculations by considering only the profile of the terrain along the great-circle arc between the bases of the transmitting and receiving antennas. The above discussion assumed that there is no very prominent terrain feature, such as a mountain-side, off the great-circle arc.

Before considering the method of fitting a circle to the profile along this particular great-circle arc, it will be

desirable to digress a little and consider the effect of air refraction on the calculations. Allowance for the effect of air refraction is ordinarily made by using an earth with effective radius $4/3$ of its actual value. In the present calculations we have made refinements on this procedure by using the actual gradient of refractive index as observed in Colorado in February and have used a value of $k = 1.231$ instead of $4/3$. This value of k was determined by Mr. Bradford Bean of the National Bureau of Standards^{14/}, and figures 40 and 41 give similar data for February and for August as determined from the Weather Bureau Ratner report at points throughout the United States. It is interesting to note the relatively high values of k along the coastal areas of the country.

The effective value of $k_t a$ which includes both the effects of irregular terrain and of atmospheric bending may be obtained by the following formula^{15/} which is derived in Appendix II.

$$\frac{1}{k_t a} = \frac{1}{k_p a} + \frac{1}{ka} - \frac{1}{a} \quad (10)$$

where a is the actual radius of the earth and $k_p a$ is the effective radius of the actual terrain.

The receiving site for the measurements discussed in this paper is at a distance of 49.3 miles as shown on figure 42. We see on this figure that the radiation from the transmitter at a height of about 8800 feet above sea level will illuminate all of the terrain from the base of the transmitting antenna out to a point beyond the base of the receiving antenna. In fact, on figure 38 we saw that the terrain would be illuminated by the transmitting antenna out to its horizon at a distance of 56 miles. Thus the condition for the use of our space-wave formula is satisfied. Note further on figure 42 that, although all of this terrain is illuminated, only that portion of it which is within line of sight of the receiving antenna will contribute appreciably to the reflected wave intensity at the receiver. Consequently we will, somewhat arbitrarily, assume that only this part of the terrain which is within line of sight of the receiving antenna plays a significant role in the reflection process. The final justification for making this somewhat arbitrary, although physically plausible,* assumption will be

* The waves reradiated from that part of the terrain beyond the receiver (low terminal) horizon may be expected to be comparatively weak on arrival at the receiving antenna due to their diffraction on propagation over this bulge of the earth.

provided by the degree of agreement between the measured and calculated transmission losses.

This particular part of the terrain is shown in more detail on figure 43. This also shows how the distance to the horizon of the receiving antenna was determined. The next step in our calculations involves the fitting of a circle to only that part of the terrain from the receiving antenna out to the receiver horizon. It should be noted that there are two purposes for determining an equivalent curved surface in the neighborhood of the bounce point of the ground-reflected ray path: (1) it is used to determine the precise location of this bounce point, i.e., the location of that point on the surface such that the ray path satisfies Snell's law, and (2) it is used to determine the surface curvatures k_t and k_r at this bounce point. We have already shown that what happens to the equivalent surface at points far removed from this bounce point is immaterial and, in fact, in the example used to illustrate our formula the transmitting antenna actually lies below the extrapolation of this equivalent surface back to the transmitter location. It is shown in Appendix II that fitting a circle is equivalent to fitting a second-degree polynomial to the terrain, at least for the range of terrain curvatures likely to be encountered in practice. The fitting of this second-degree polynomial may conveniently be done by the method of least squares.

Returning now to figure 42, we may extend this second-degree polynomial back to the transmitting antenna. This dashed curve may now be corrected for the effects of the curvature of the earth and the effects of air refraction to give the solid curve which is now taken to be the great circle on the equivalent spherical surface passing through only that portion of the terrain assumed to be involved in the reflection and relative to which our space-wave transmission-loss calculations are to be made. It will be noted in this particular case that our transmitting antenna is actually below this equivalent spherical surface, which indicates an actually negative transmitting antenna height, h_2 . This, however, will not cause any difficulty in our calculations since it is the positive height, h_2' , above the plane tangent at the bounce point which enters directly into the space-wave calculations. It is shown in Appendix II that the formula for the effective radius of curvature, k_t , of this circular arc may be determined by:

$$\frac{1}{k_t} = \frac{1}{k} - 1.4995 c \quad (11)$$

where c is the coefficient of y^2 in the polynomial expression fitting the terrain:

$$h = h_{10} + b y + c y^2 \quad (12)$$

In the above equation h is expressed in feet above sea level and y is the geodesic distance along the great-circle arc from the receiving site expressed in statute miles.

The value of $k_t a$ enters directly into the transmission loss calculations only in connection with the formula (9) for the divergence (or convergence) factor. In this formula $k_t a$ denotes the radius of curvature of the curved surface in the plane of propagation while $k'_t a$ denotes the radius of curvature of the surface in the plane normal to the plane of propagation.^{13/} Since D is appreciably different from unity only near grazing incidence so that $\sin \psi$ is quite small, it follows that the factor in the round brackets of (9) will be of no practical importance. Thus we conclude that only the curvature of the reflecting surface in the plane of propagation will appreciably influence the intensity of the ground-reflected wave and normally we need not even investigate the surface curvature normal to the propagation path.

The only factors in our transmission loss formula which have not yet been discussed are the ground-reflection coefficient magnitude, $|R|$, and phase, C . The measurements discussed in this paper have all been made with horizontal polarization for which $|R| \approx 1$ and $C \approx \pi$. This completes the description of our formula and we may now use it for a comparison with our measured transmission losses. These are given in the following table. Unfortunately only three measurements are now available. These three correspond to transmission from the upper site at Cheyenne Mountain to the first receiving site which is at a distance of 49.3 miles. All of the other presently available Cheyenne Mountain measurements correspond to points beyond the "space wave line of sight" as defined earlier. For this path $k = 1.231$ and $k_t = -0.3062$.

| f_{mc} | F_m (db) | F_c (db) | $(F_m - F_c)$ db | $\frac{4\pi \Delta h \sin \psi}{\lambda}$ | h_2' (ft) | h_1' (ft) |
|----------|------------|------------|------------------|---|-------------|-------------|
| 100 | 121.21 | 117.00 | 4.21 | 0.198 | 1603 | 12.78 |
| 192.8 | 120.27 | 118.16 | 2.11 | 0.397 | 1668 | 11.45 |
| 1046 | 102.31 | 95.40 | 6.91 | 1.866 | 1423 | 40.70 |

It will be noted that the measured transmission losses exceed the calculated losses by an amount varying up to nearly 7 db for this particular path. Since our theoretical formula is for a smooth spherical surface, it may be that the deviation between the measured and calculated values arises from the irregularities in the terrain height relative to the spherical surface.

We see on figure 43 that the actual terrain departs from the dashed line used to represent it by as much as $\Delta h = 25$ feet at a distance of 4 miles from the receiving location. A departure of this magnitude, Δh , will cause the phase of the reflected wave from this particular portion of the terrain to change at the receiving location by an amount $4\pi\Delta h \sin \psi/\lambda$. We may expect our formula to be increasingly inaccurate the larger the value of this factor. This is Rayleigh's criterion of roughness and it appears from our particular results that $(4\pi\Delta h \sin \psi/\lambda)$ must be of the order of 1/10 or less if we are to obtain agreement between measurements and theory to better than, say, one db. As additional measurements are made and compared with the theory a still better estimate of the permissible height deviations will be obtained.

It is of interest to determine the influence of air refraction on our calculated transmission losses. An idea of this effect may be obtained by calculating the additional transmission loss for $k = 1$ as compared to the value in the table which corresponds to $k = 1.231$. At 100 Mc the calculated value of this additional loss is equal to 0.96 db, at 192.8 Mc is equal to 1.23 db and at 1047 Mc is equal to 3.06 db.

At large distances our transmission-loss formula may be written in an approximate form which makes possible a better appreciation of the influence of the various factors. Thus assume that $g_{1d} \approx g_{1r}$ and $g_{2d} \approx g_{2r}$, let $d \approx d_1 + d_2$, $D \approx |R| \approx 1$, $\theta \approx 4\pi h_1' h_2'/\lambda d$, and $\theta \ll \pi/2$. Then we obtain for L_c :

$$L_c \approx 20 \log_{10} (d^2/h_1' h_2') - 10 \log_{10} g_1 - 10 \log_{10} g_2 \quad (13)$$

In the above formula, d , h_1' and h_2' are to be expressed in the same units. With d expressed in statute miles and h_1' and h_2' expressed in feet, this becomes:

$$L_c = 148.9 + 40 \log_{10} d - 20 \log_{10} h_1' - 20 \log_{10} h_2' - 10 \log_{10} g_1 - 10 \log_{10} g_2 \quad (14)$$

It is of interest to note that the frequency does not appear in this approximate expression for the "within line of sight" space wave transmission loss; we have already seen that this type of formula tends to be applicable when Rayleigh's criterion of roughness is satisfied and we may therefore conclude that the additional losses observed at the higher frequencies arise from the increasingly important effects of the departures of the terrain from a smooth spherical surface.

It is of interest to attempt a reconciliation of this formula with the observed transmission loss results discussed by Norton, Schulkin and Kirby in Reference C to the FCC Ad Hoc Committee report.^{16/} In that report it was found that the observed transmission loss departed substantially from the values calculated using the FCC 2-to-10-mile rule for determining the transmitting antenna height. These departures, when expressed in db, appeared to be normally distributed about a mean which increased with increasing frequency and decreased with increasing distance. This behavior of the mean is exactly what would be expected in view of the form of Rayleigh's criterion of roughness. The variance of the normal distribution was not found to behave as would be expected from the form of this criterion of roughness, however, and we must look further for an explanation of this characteristic of the observations. It is believed that a clue to the explanation of the variance lies in the coefficients h_{10} , b , and c in our polynomial fitting the terrain. These three coefficients will vary as we go from one receiving site to the next and, in fact, we may suppose each of these three coefficients to be random, independent, normally distributed, variables. The expected mean value of h_{10} will be the average of the heights above sea level of the actual terrain for all receiving locations while the expected mean values of b and c will each be zero. We will now show that the variance of these three coefficients provides a plausible explanation of the observed log normal distribution of the transmission loss.

The effective height, h_2' , of the transmitting antenna may be approximately expressed as follows:

$$h_2' \approx h_{2s} - h_{10} - d \left\{ b + cd_1 + \frac{2d_2}{3k} \right\} \quad (15)$$

where h_{2s} is the height of the transmitting antenna above sea level. In this formula, all heights are expressed in feet while the distances are expressed in miles. Equation (15) may be derived by passing a plane through the points on the spherical

surface corresponding to $y = 0$ and $y = d_1$ and assuming that this plane is a good approximation to the reflection plane tangent to the spherical surface at $y = d_1$. The approximation involved in this assumption is better the smaller the value of the ratio (d_1/d_2) . Assuming that h_{10} , b , and c are each normally distributed variables, we see that h_2' will also be normally distributed with a mean value,

$$\overline{h_2'} = h_{2s} - \overline{h_{10}} - \frac{2dd_2}{3k} \equiv h_f - \frac{2dd_2}{3k} \quad (16)$$

This mean value may be interpreted as follows:

The difference $(h_{2s} - \overline{h_{10}})$ simply represents the height of the transmitting antenna above the average level of the terrain in the service area; h_{10} is not the actual terrain height at the receiving location but its average value will nevertheless closely approximate the average height of the terrain above sea level. We will represent this height by h_f , the subscript f being used since this height is closely allied to the FCC transmitting antenna height determined from the FCC 2-to-10-mile rule. The term $2dd_2/3k$ gradually reduces the value of h_2' to zero as the distance increases and represents the systematic effects of the curvature of the earth and of air refraction. However, as h_2' approaches zero we reach the region for which our formula is no longer directly applicable and we must resort to interpolation between these results and those obtained by a diffraction formula. Using this expression for h_2' and writing $h_1' = h_{1s} - h_{10}$ we may now express our formula for transmission loss as follows:

$$L_c \approx 148.8 + 40 \log_{10} d - 20 \log_{10} \left[(h_{1s} - \overline{h_{10}}) \left(1 - \frac{h_{10} - \overline{h_{10}}}{h_{1s} - \overline{h_{10}}} \right) \right] \\ - 10 \log_{10} \epsilon_1 - 10 \log_{10} \epsilon_2 \\ - 20 \log_{10} \left[\left(h_f - \frac{2dd_2}{3k} \right) \left(1 - \frac{(h_{10} - \overline{h_{10}}) + d(b + cd_1)}{h_f - \frac{2dd_2}{3k}} \right) \right] \quad (17)$$

$$\begin{aligned}
 L_c = & 148.8 + 40 \log_{10} d - 20 \log_{10} (h_{1s} - \overline{h_{10}}) - 10 \log_{10} g_1 \\
 & - 10 \log_{10} g_2 - 20 \log_{10} \left(h_f - \frac{2dd_2}{3k} \right) \\
 & + 8.68 \left[\frac{h_{10} - \overline{h_{10}} + d(b + cd_1)}{h_f - \frac{2dd_2}{3k}} + \frac{h_{10} - \overline{h_{10}}}{h_{1s} - \overline{h_{10}}} \right] \quad (18)
 \end{aligned}$$

Note that $(h_{1s} - \overline{h_{10}})$ may be considered to be the height of the lower antenna above the local terrain, i.e., 30 feet in the case of the FCC studies. The assumption is made in going from (17) to (18) that each of the terms in the square brackets in (18) is small with respect to unity and use is then made of the approximation $\log_e (1-X) \approx -X$. The quantity in the square brackets above is, in accordance with our assumptions, a random variable, normally distributed about a mean of zero. Thus it provides an explanation of the observed fact that transmission loss is log normally distributed with respect to receiving antenna location; i.e., that L is a normally distributed variable. Let σ_{h1} , σ_b , and σ_c represent the variances of the independent random variables $(h_{10} - \overline{h_{10}})$, b , and c , respectively, and we find for the standard deviation of this variable term, expressed in db:

$$\sigma_h = \frac{8.68}{h_f - \frac{2dd_2}{3k}} \left\{ \sigma_{h1}^2 \left[1 + \frac{h_f - \frac{2dd_2}{3k}}{h_{1s} - \overline{h_{10}}} \right]^2 + d^2 (\sigma_b^2 + d_1^2 \sigma_c^2) \right\}^{1/2} \quad (19)$$

We see that this variance will increase with increasing distance from the transmitter. Remembering that the component of variance due to roughness decreases with increasing distance, we see that the combination of that roughness variance with the above value may result in an over-all variance which will be more or less independent of the distance as has been observed in practice.^{16/}

Conclusion

It is considered desirable that (7) and (19) be used for a study of the nature of space-wave propagation over irregular terrain. It is believed that these two equations provide a method of separating the systematic from the random effects of terrain irregularities.

APPENDIX I - CHEYENNE MOUNTAIN TRANSMISSION LOSS DATA

| Distance in Miles | Transmitter and Location | Months Recorded | P_t in db above 1 watt | G_t in db | ERP in db |
|----------------------|---|---------------------------------|-----------------------------|-------------|---------------------------------------|
| | | | | | above 1 watt ($P_t + G_t - L_t$) |
| Frequency in Mc | Recording Agency and Location | Hours Recorded | L_t in db | G_r in db | h_t in feet h_r in feet |
| 49.3 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Feb. 29, 1952 | 36.021 | 26.000 | 61.806 |
| 1046 Mc | CRPL Kendrick, Colo. | 24 hrs/day | 0.215 | 2.15 | 8800' **** 42.67' *** |
| 49.3 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 31, 1952 | 33.010 | 10.40 | 43.106 |
| 192.8 Mc | CRPL Kendrick, Colo. | 24 hrs/day | 0.304 | 2.15 | 8800' **** 17.50' *** |
| 49.3 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 31, 1952 | 33.010 | 10.40 | 43.106 |
| 100 Mc | CRPL Kendrick, Colo. | 24 hrs/day | 0.304 | 2.15 | 8800' **** 18.75' *** |

* height of antenna above 2-10-mile average terrain in the direction of the other antenna.

** height of antenna above 2-10-mile average surrounding terrain.

*** height of antenna above ground.

**** height of antenna above mean sea level.

x transmitting antenna is greater than or equal to this figure. Given in db above an isotropic antenna.

| Distance in Miles | Transmitter and Location | Months Recorded | P_t in db above 1 watt | G_t in db | ERP in db above 1 watt ($P_t + G_t - L_t$) |
|----------------------|---|---------------------------------|-----------------------------|-------------|--|
| Frequency in Mc | Recording Agency and Location | Hours Recorded | L_t in db | G_r in db | h_t in feet h_r in feet |
| 49.4 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 7, 1952 | 33.010 | 10.60 | 43.425 |
| 210.4 Mc | CRPL Kendrick, Colo. | 24 hrs/day | 0.185 | 2.15 | 7700' **** 35.50' *** |
| 49.4 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 7, 1952 | 33.010 | 9.25 | 42.171 |
| 92 Mc | CRPL Kendrick, Colo. | 24 hrs/day | 0.089 | 2.15 | 7700' **** 36.75' *** |
| 70.2 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 7, 1952 | 33.010 | 9.25 | 42.171 |
| 92 Mc | CRPL Karval, Colo. | 24 hrs/day | 0.089 | 2.15 | 7700' **** 36.75' *** |
| 70.2 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 31, 1952 | 33.010 | 9.98 | 42.886 |
| 100 Mc | CRPL Karval, Colo. | 24 hrs/day | 0.104 | 2.15 | 8800' **** 18.75' *** |

| Distance in Miles | Transmitter and Location | Months Recorded | P_t in db above 1 watt | G_t in db | ERP in db above 1 watt ($P_t + G_t - L_t$) |
|----------------------|---|--|-----------------------------|-------------|--|
| Frequency in Mc | Recording Agency and Location | Hours Recorded | L_t in db | G_r in db | h_t in feet h_r in feet |
| 70.2 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 31, 1952 (834 hrs) | 33.010 | 10.40 | 43.106 |
| 192.8 Mc | CRPL Karval, Colo. | 24 hrs/day | 0.304 | 2.15 | 8800' **** 17.50' *** |
| 70.2 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Feb. 29, 1952 (207 hrs) | 36.021 | 26.00 | 61.806 |
| 1046 Mc | CRPL Karval, Colo. | 24 hrs/day | 0.215 | 2.15 | 8800' **** 42.67' *** |
| 96.6 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 31, 1952 | 33.010 | 9.98 | 42.886 |
| 100 Mc | CRPL Haswell, Colo. | 24 hrs/day | 0.104 | 2.15 | 8800' **** 18.75' *** |
| 96.6 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 31, 1952 | 33.010 | 10.40 | 43.106 |
| 192.8 Mc | CRPL Haswell, Colo. | 24 hrs/day | 0.304 | 2.15 | 8800' **** 17.50' *** |

| Distance in Miles | Transmitter and Location | Months Recorded | P_t in db above 1 watt | G_t in db | ERP in db above 1 watt ($P_t + G_t - L_t$) |
|----------------------|---|---------------------------------|-----------------------------|-------------|--|
| Frequency in Mc | Recording Agency and Location | Hours Recorded | L_t in db | G_r in db | h_t in feet h_r in feet |
| 96.6 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Feb. 29, 1952 | 33.021 | 26.00 | 61.806 |
| 1046 Mc | CRPL Haswell, Colo. | 24 hrs/day | 0.215 | 2.15 | 8800' **** 42.67' *** |
| 96.8 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 7, 1952 | 33.010 | 10.60 | 43.425 |
| 210.4 Mc | CRPL Haswell, Colo. | 24 hrs/day | 0.185 | 2.15 | 7700' **** 35.50' *** |
| 96.8 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 7, 1952 | 33.010 | 9.25 | 42.171 |
| 92 Mc | CRPL Haswell, Colo. | 24 hrs/day | 0.089 | 2.15 | 7700' **** 36.75' *** |
| 226.6 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Feb. 23, 1952- Feb. 25, 1952 | 36.021 | 26.00 | 61.806 |
| 1046 Mc | CRPL Garden City, Kansas | 24 hrs/day | 0.215 | 2.15 | 8800' **** 42.67' *** |

| Distance in Miles | Transmitter and Location | Months Recorded | P_t in db above 1 watt | G_t in db | ERP in db above 1 watt ($P_t + G_t - L_t$) |
|----------------------|---|---------------------------------|-----------------------------|-------------|--|
| Frequency in Mc | Recording Agency and Location | Hours Recorded | L_t in db | G_r in db | h_t in feet h_r in feet |
| 226.6 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 31, 1952 | 33.01 | 9.98 | 41.886 |
| 100 Mc | CRPL Garden City, Kansas | 24 hrs/day | 0.104 | 2.15 | 8800' **** 18.75' *** |
| 226.6 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 31, 1952 | 33.01 | 10.40 | 43.106 |
| 192.8 Mc | CRPL Garden City, Kansas | 24 hrs/day | 0.304 | 2.15 | 8800' **** 17.50' *** |
| 226.6 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Jan. 20, 1952- Mar. 7, 1952 | 33.010 | 9.250 | 42.171 |
| 92 Mc | CRPL Garden City, Kansas | 24 hrs/day | 0.089 | 2.15 | 7700' **** 36.75' *** |
| 393.5 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Feb. 5, 1952- Mar. 7, 1952 | 33.101 | 9.25 | 42.171 |
| 92 Mc | CRPL Anthony, Kansas | Intermittent periods | 0.089 | 12.15 | 7700' **** 39' *** |

| <u>Distance in Miles</u> | <u>Transmitter and Location</u> | <u>Months Recorded</u> | <u>P_t in db above 1 watt</u> | <u>G_t in db</u> | <u>ERP in db above 1 watt (P_t + G_t - L_t)</u> |
|------------------------------|---|--------------------------------|---|----------------------------|---|
| <u>Frequency in Mc</u> | <u>Recording Agency and Location</u> | <u>Hours Recorded</u> | <u>L_t in db</u> | <u>G_r in db</u> | <u>h_t in feet h_r in feet</u> |
| 393.5 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Feb. 5, 1952- Mar. 11, 1952 | 33.010 | 9.98 | 42.886 |
| 100 Mc | CRPL Anthony, Kansas | Intermittent periods | 0.104 | 12.15 | 8800' **** 39' *** |
| 393.5 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Feb. 5, 1952- Mar. 11, 1952 | 33.010 | 9.98 | 42.886 |
| 100 Mc | CRPL Anthony, Kansas | Intermittent periods | 0.104 | 15.55 | 8800' **** 39' *** |
| 393.5 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Feb. 5, 1952- Feb. 18, 1952 | 33.010 | 10.40 | 43.106 |
| 192.8 Mc | CRPL Anthony, Kansas | Intermittent periods | 0.304 | 13.25 | 8800' **** 39' *** |
| 393.5 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Feb. 5, 1952- Feb. 20, 1952 | 36.021 | 26.00 | 61.806 |
| 1046 Mc | CRPL Anthony, Kansas | Intermittent periods | 0.215 | 26.15 | 8800' **** 30' *** |

| Distance in Miles | Transmitter and Location | Months Recorded | P_t in db above 1 watt | G_t in db | ERP in db above 1 watt ($P_t + G_t - L_t$) |
|----------------------|---|---------------------------------|-----------------------------|-------------|--|
| Frequency in Mc | Recording Agency and Location | Hours Recorded | L_t in db | G_r in db | h_t in feet h_r in feet |
| 616.3 mi | (CRPL) Cheyenne Mt., Colo. Springs, Colo. | Feb. 21, 1952- Feb. 24, 1952 | 33.010 | 9.98 | 42.886 |
| 100 Mc | CRPL Fayetteville, Ark. | Intermittent periods | 0.104 | 15.55 | 8800' **** 38' *** |
| | | | | | |
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APPENDIX II

SPHERICAL SURFACE GEOMETRY INCLUDING AN ALLOWANCE FOR
ATMOSPHERIC REFRACTION

The following relations may be determined from figure 44:

$$\cos \theta = \frac{a}{a + h} \quad (20)$$

$$\theta = \frac{d}{a} \quad (21)$$

$$h = a(\sec \theta - 1) = \frac{d^2}{2a} \left(1 + \frac{5d^2}{12a^2} + \dots \right) \quad (22)$$

Use of the first term only in (22) above introduces an error in estimation of h of less than 0.1 percent for $d < (a/20)$, i.e. for $a = 4000$ miles, $d < 200$ miles.

Similarly we may obtain:

$$h_p = \frac{d^2}{2k_p a} \quad (23)$$

$$h_t = \frac{d^2}{2k_t a} \quad (24)$$

In the above a denotes the actual radius of the earth which we take to be equal to its average value 3958.74 miles. Note that, at the limit of applicability of the first term in (22), $\theta < 2.8^\circ$ and this should be kept in mind in interpreting figure 44 on which θ is, for convenience, shown to be 45° . For $\theta = 2.8^\circ$ all of the circled points on figure 44 will lie very nearly on a vertical line. In the above equations, the heights and distances are to be expressed in the same units. In (12), however, h is expressed in feet and y in miles. Consequently, when used in the above equations, the curvature of the terrain relative to a plane tangent at the bounce point of the ground-reflected wave is equal to:

$$\frac{1}{k_p a} = \frac{1}{a} - \frac{2c}{5280} = \frac{1}{a} (1 - 1.4995c) \quad (25)$$

Note that the radius of curvature, $k_p a$, at the bounce point is independent of the slope of the plane tangent to the terrain at

the bounce point and is thus independent of b . This independence of k_p and b may be seen by reference to figure 44 (drawn for the case $b = 0$) if we let b vary by rotating the curve labelled sea level in the plane of the diagram about the bounce point at $d = 0$: this rotation clearly does not change the radii of curvature of either the actual terrain or the effective terrain.

It has long been recognized^{17/} that the effects of air refraction may, to a first approximation, be allowed for in transmission loss calculations at points within the line of sight by assuming that the refractive index of the atmosphere has a constant gradient (dn/dh) with height above sea level. Since (dn/dh) is assumed to be a constant, independent of h , the reference height may as well be that of the actual earth rather than sea level. The ray curvature resulting from such a constant gradient is simply $(\frac{1}{n_0} \frac{dn}{dh})$ and the effective curvature of a fictitious earth, relative to which the rays appear to be straight lines, is thus:

$$\frac{1}{ka} = \frac{1}{a} + \frac{1}{n_0} \frac{dn}{dh} \quad (26)$$

The values of k shown on figures 40 and 41 are based on (26) with a equal to the average radius of the earth but with (dn/dh) measured from the actual surface of the earth. Finally, we may obtain a fictitious curvature which allows for both the effects of air refraction and of terrain curvature relative to that of the earth simply by adding the curvature $(\frac{1}{n_0} \frac{dn}{dh})$ to the net curvature of the actual terrain as given by (25):

$$\frac{1}{k_t a} = \frac{1}{a} (1 - 1.4995c) + \frac{1}{n_0} \frac{dn}{dh} = \frac{1}{a} \left(\frac{1}{k} - 1.4995c \right) \quad (27)$$

An alternative derivation of (27), which may appeal to some, follows from the geometry of figure 44, remembering that in all of our applications, θ will be very small. If we define h_r to be the change, due to air refraction, in the effective height of the horizon, then:

$$h_r = \left[1 - \frac{1}{k} \right] \frac{d^2}{2a} \quad (28)$$

On the diagram we see that $h_t \cong h_p - h_r$, the degree of approximation arising from the higher order terms of (22). Thus, by substituting (23), (24) and (28) into this relation, we obtain:

$$\frac{d^2}{2k_t a} = \frac{d^2}{2k_p a} - \left[1 - \frac{1}{k} \right] \frac{d^2}{2a} \quad (29)$$

$$\text{or } \frac{1}{k_t} = \frac{1}{k_p} + \frac{1}{k} - 1 = \frac{1}{k} - 1.4995c \quad (30)$$

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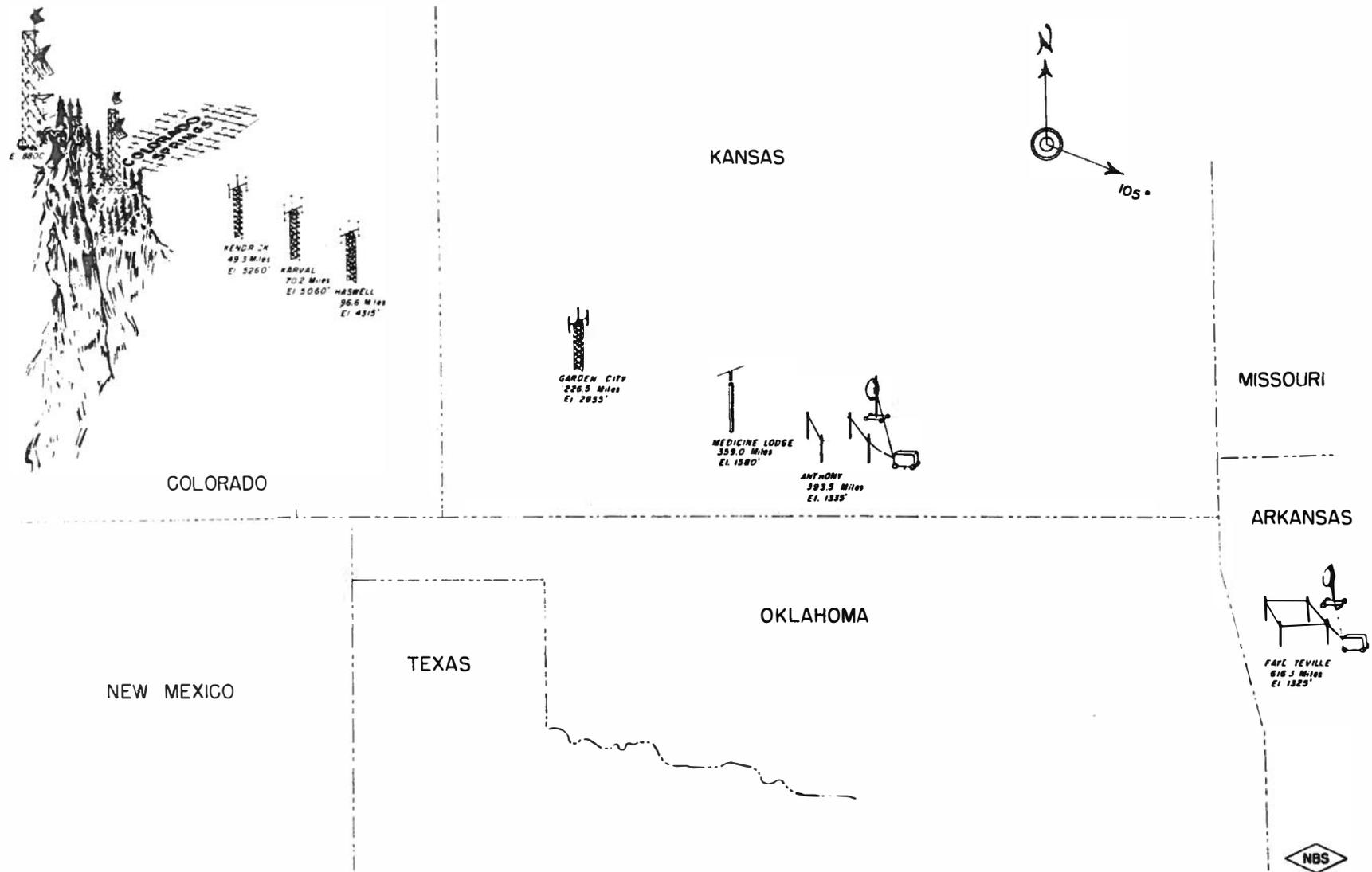


Figure 2

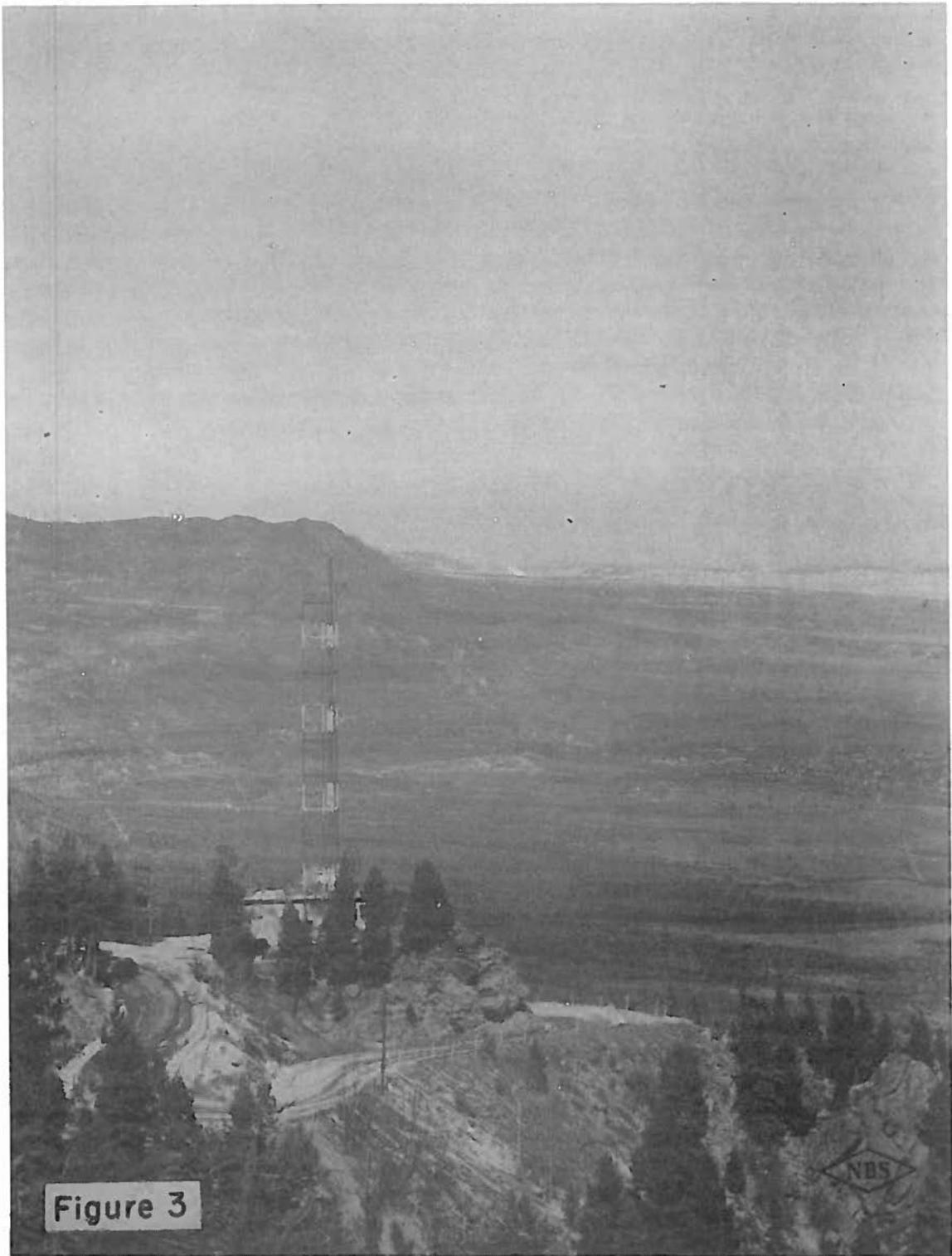


Figure 3



Figure 4

NBS

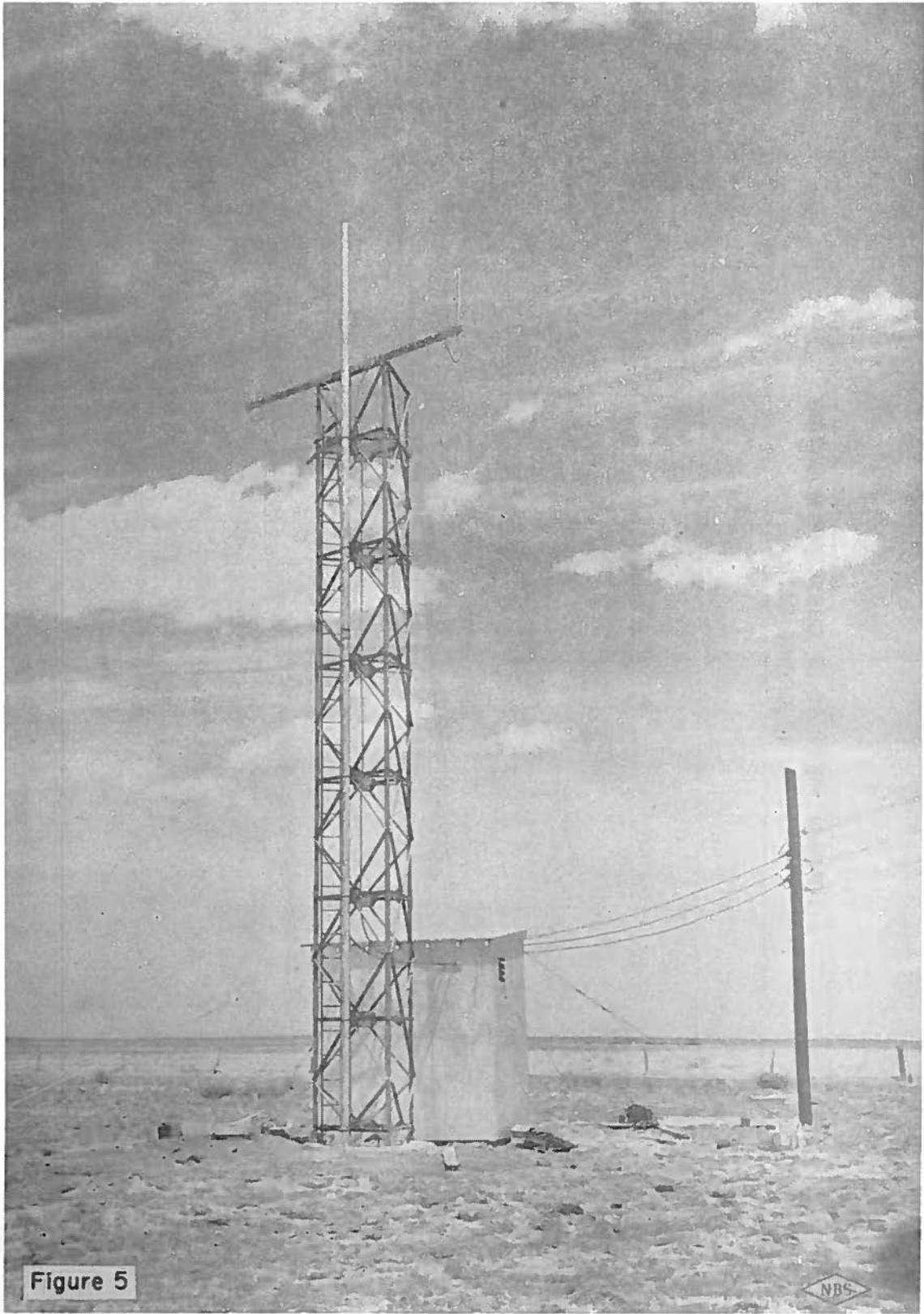


Figure 5

NBS

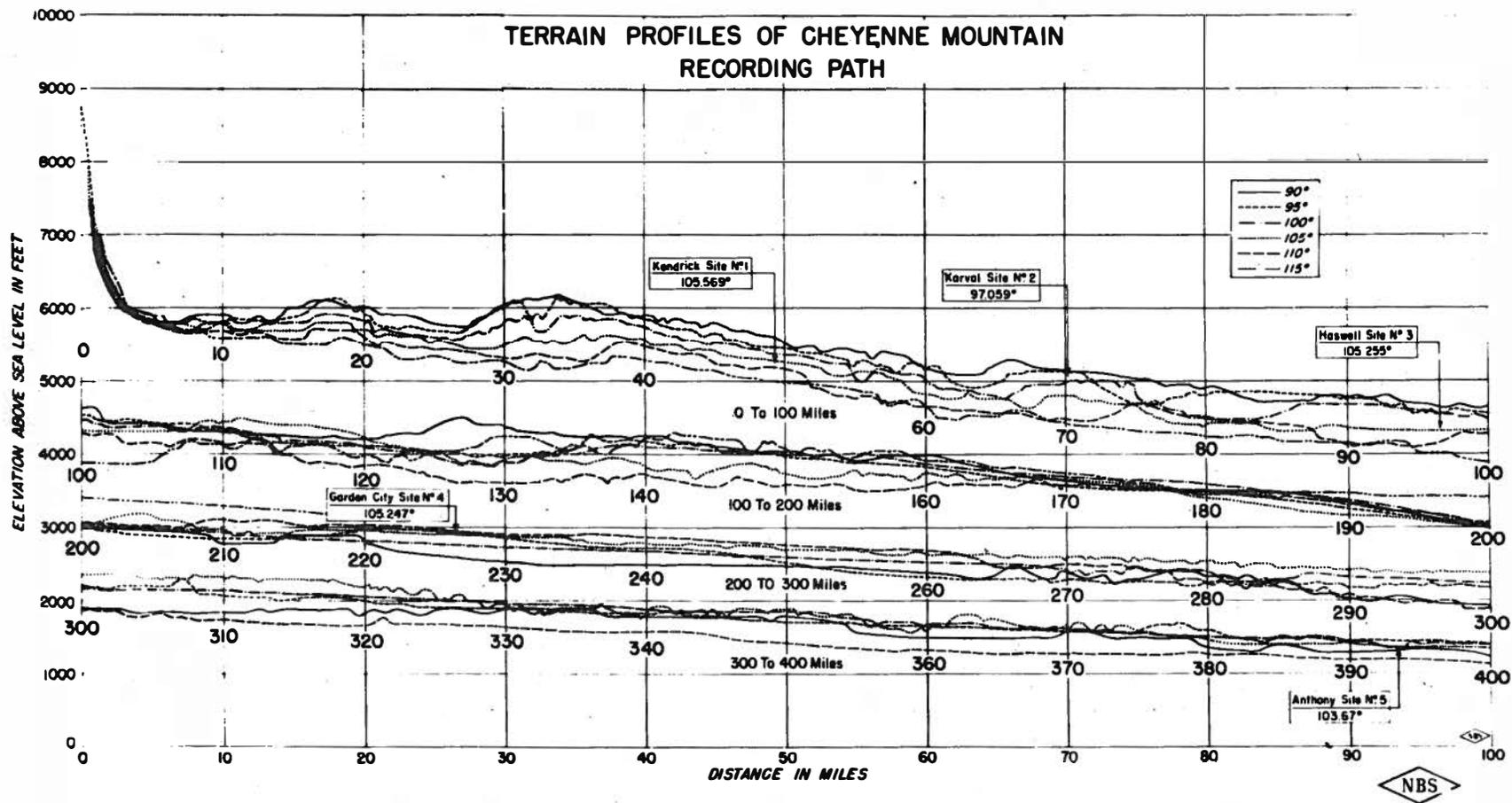


Figure 6

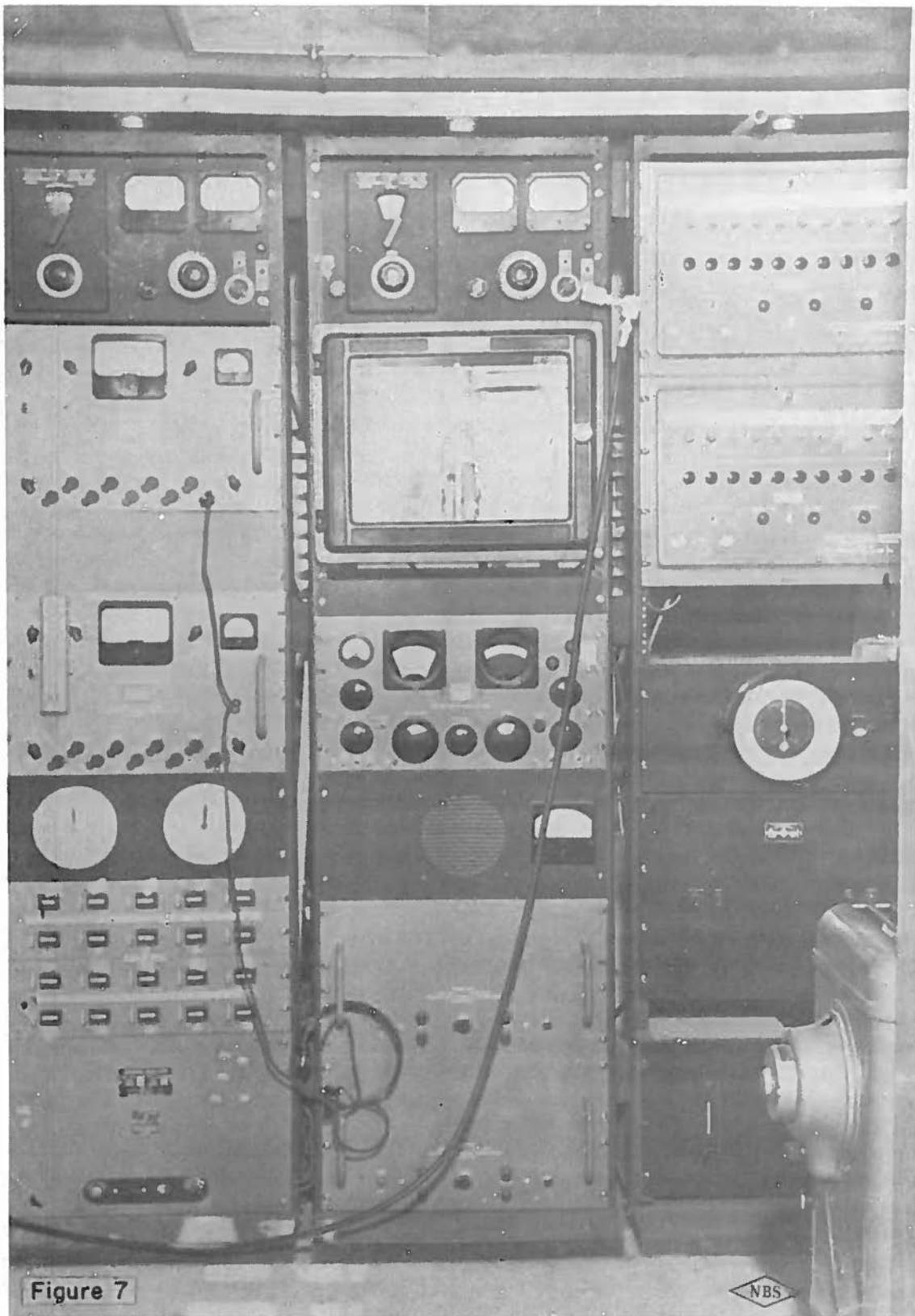


Figure 7

NBS

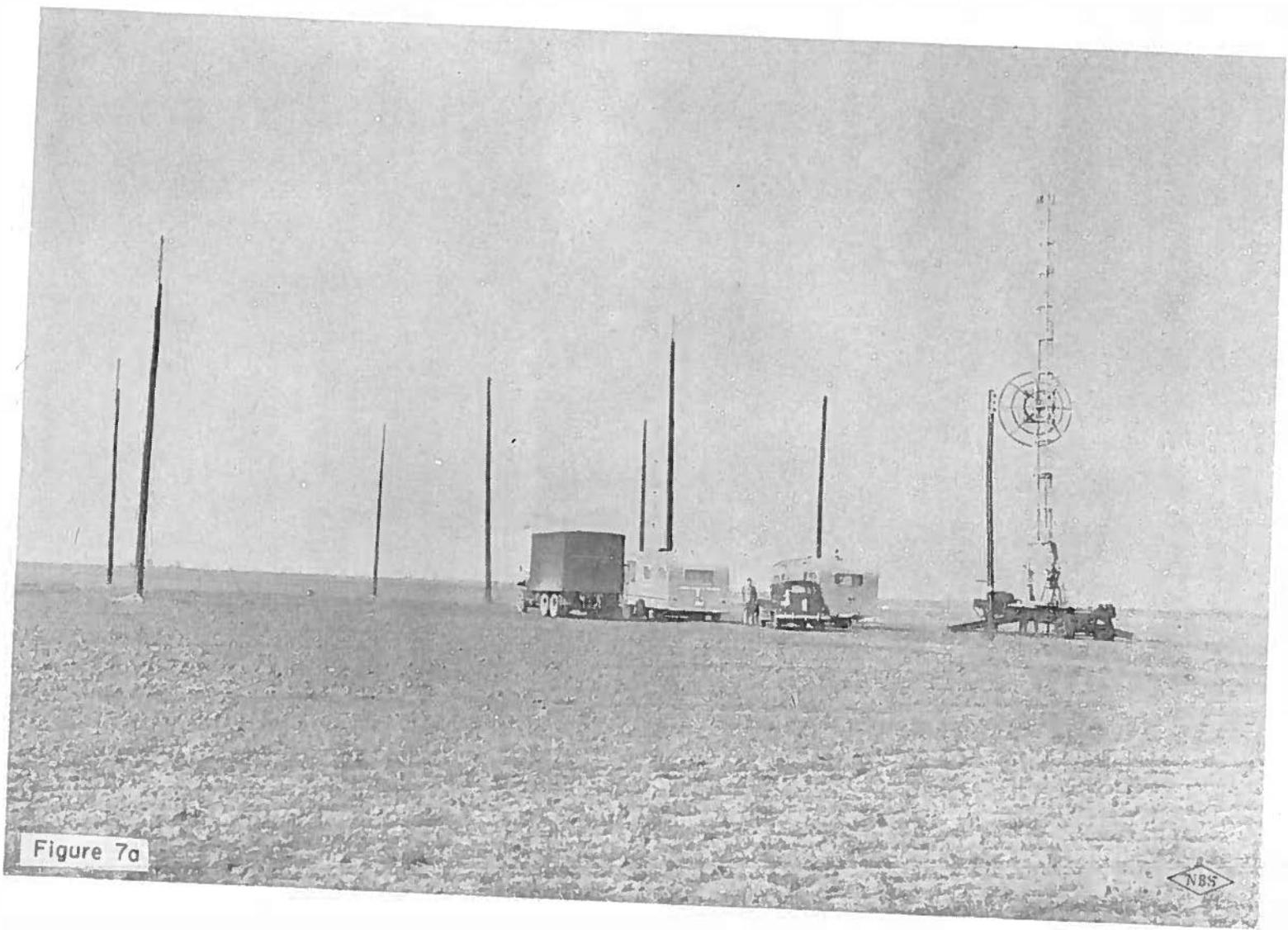


Figure 7a

NBS

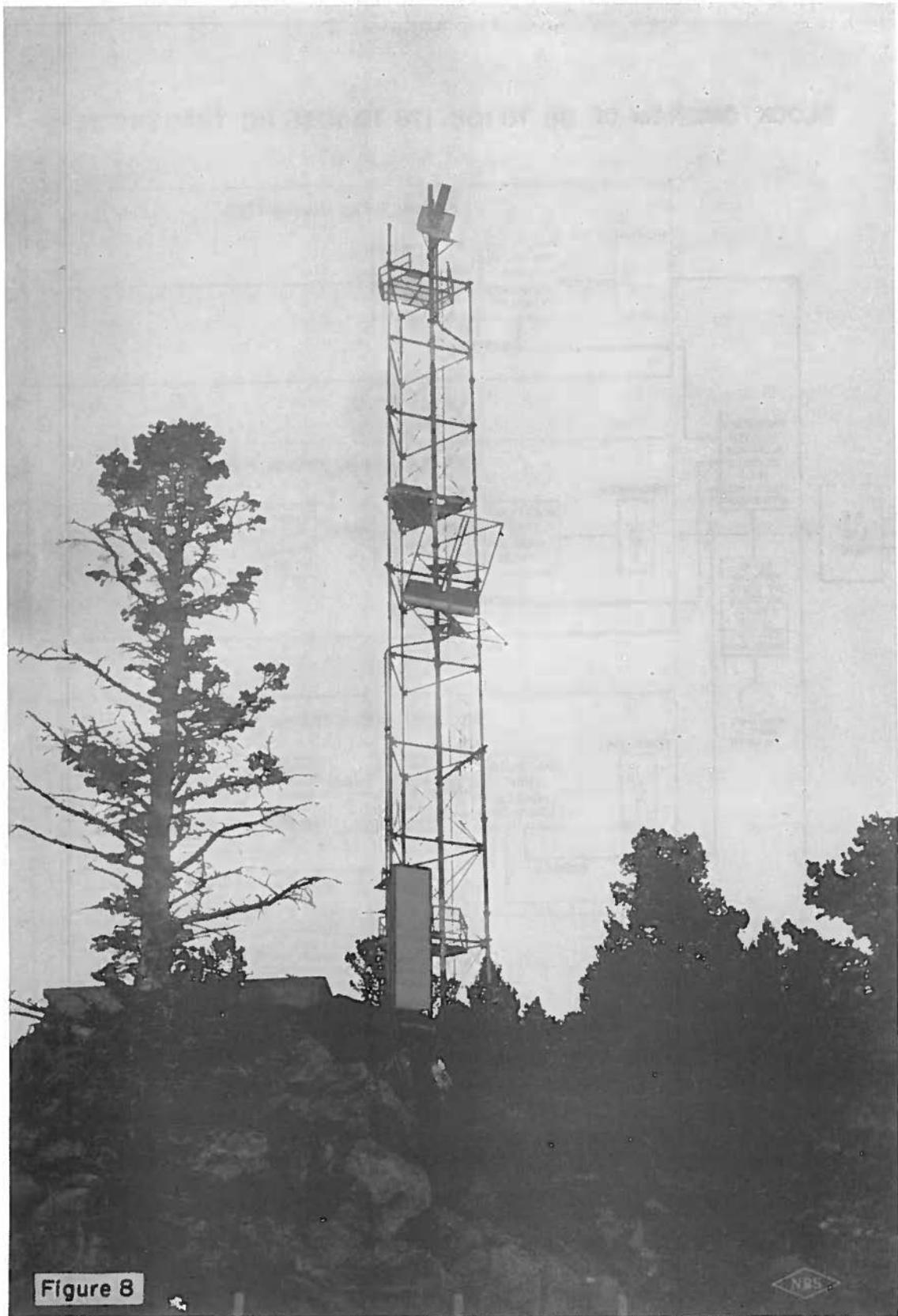


Figure 8



BLOCK DIAGRAM OF 88 TO 108, 176 TO 1056 MC TRANSMITTERS

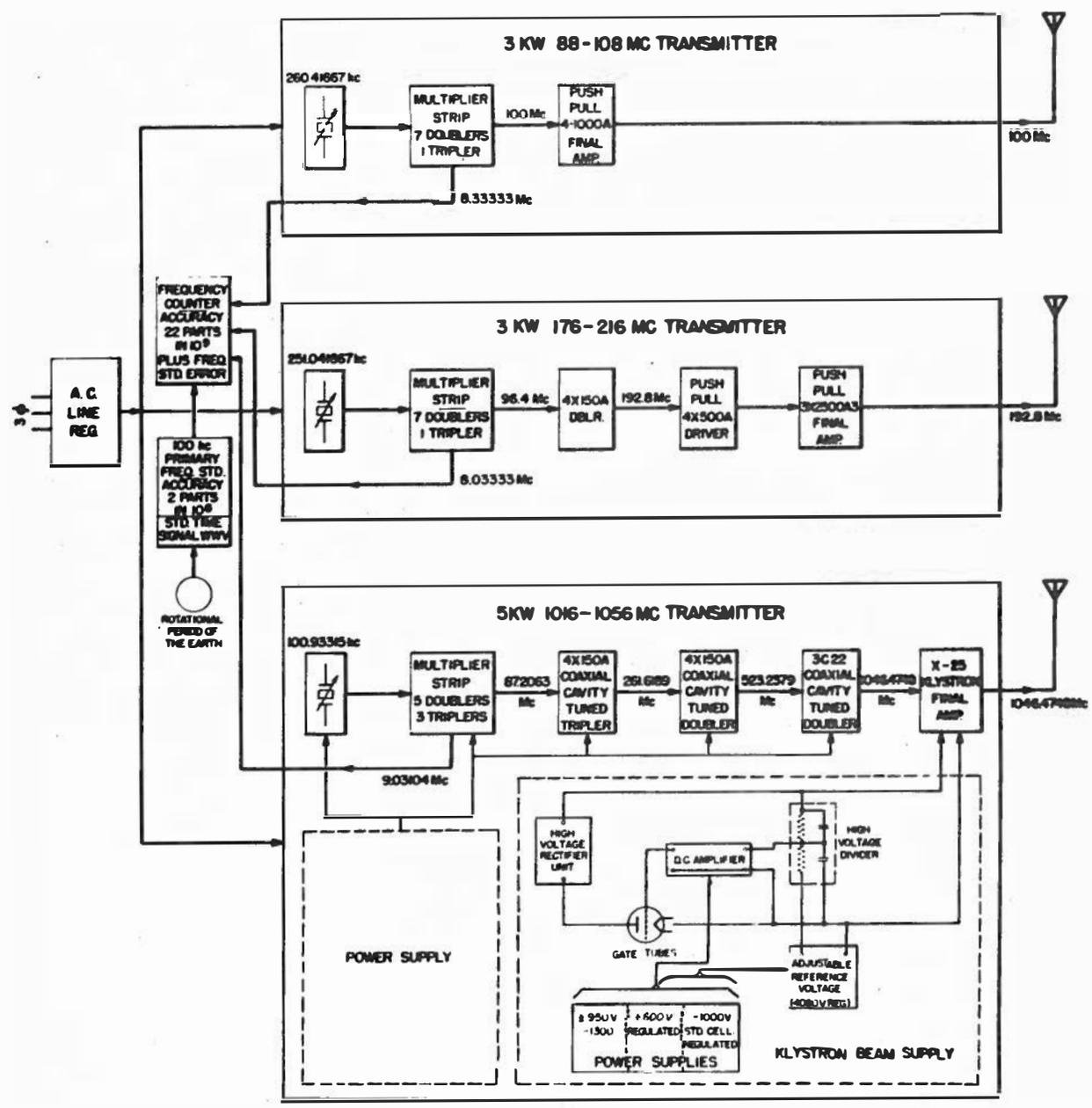


Figure 9

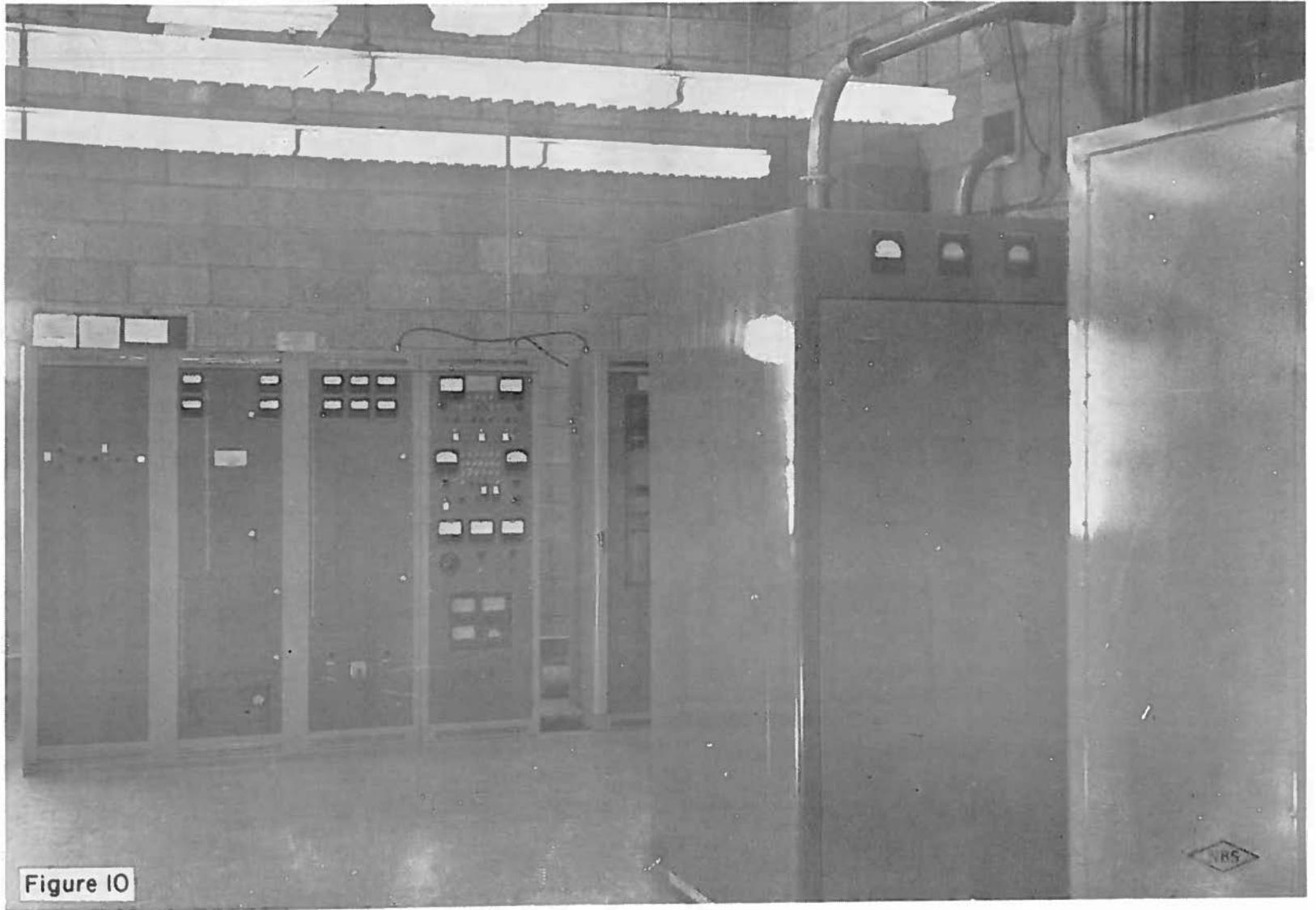
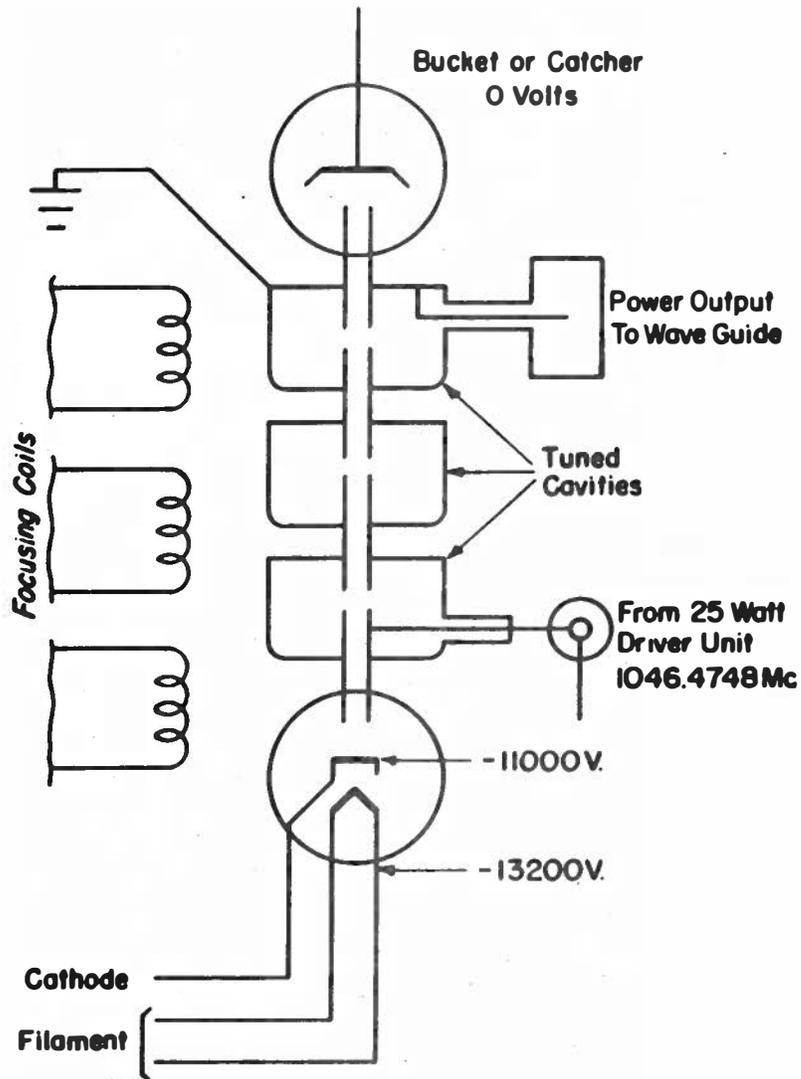


Figure 10

ARRANGEMENT OF ELEMENTS IN 1046Mc KLYSTRON TUBE



TYPICAL OPERATING CONDITIONS 1046.4748 Mc

| | | | | | | | |
|--------------------------------|--|---------------|-------------------|---------------|------------------|------------|------------------|
| <i>Beam Voltage</i> | <i>11000 Volts</i> | | | | | | |
| <i>Beam Current</i> | <i>1.55 Amps.</i> | | | | | | |
| <i>Focusing Coils</i> | <table style="border-left: 1px solid black; border-right: 1px solid black; padding-left: 5px;"> <tr> <td style="padding-right: 5px;"><i>Bottom</i></td> <td><i>1.34 Amps.</i></td> </tr> <tr> <td style="padding-right: 5px;"><i>Center</i></td> <td><i>.88 Amps.</i></td> </tr> <tr> <td style="padding-right: 5px;"><i>Top</i></td> <td><i>.29 Amps.</i></td> </tr> </table> | <i>Bottom</i> | <i>1.34 Amps.</i> | <i>Center</i> | <i>.88 Amps.</i> | <i>Top</i> | <i>.29 Amps.</i> |
| <i>Bottom</i> | <i>1.34 Amps.</i> | | | | | | |
| <i>Center</i> | <i>.88 Amps.</i> | | | | | | |
| <i>Top</i> | <i>.29 Amps.</i> | | | | | | |
| <i>Bombarder Voltage</i> | <i>2200 Volts</i> | | | | | | |
| <i>Continuous Power Output</i> | <i>4 KW</i> | | | | | | |



Figure 11

CIRCUIT DIAGRAM OF IO46 MC KLYSTRON AMPLIFIER HIGH VOLTAGE RECTIFIER

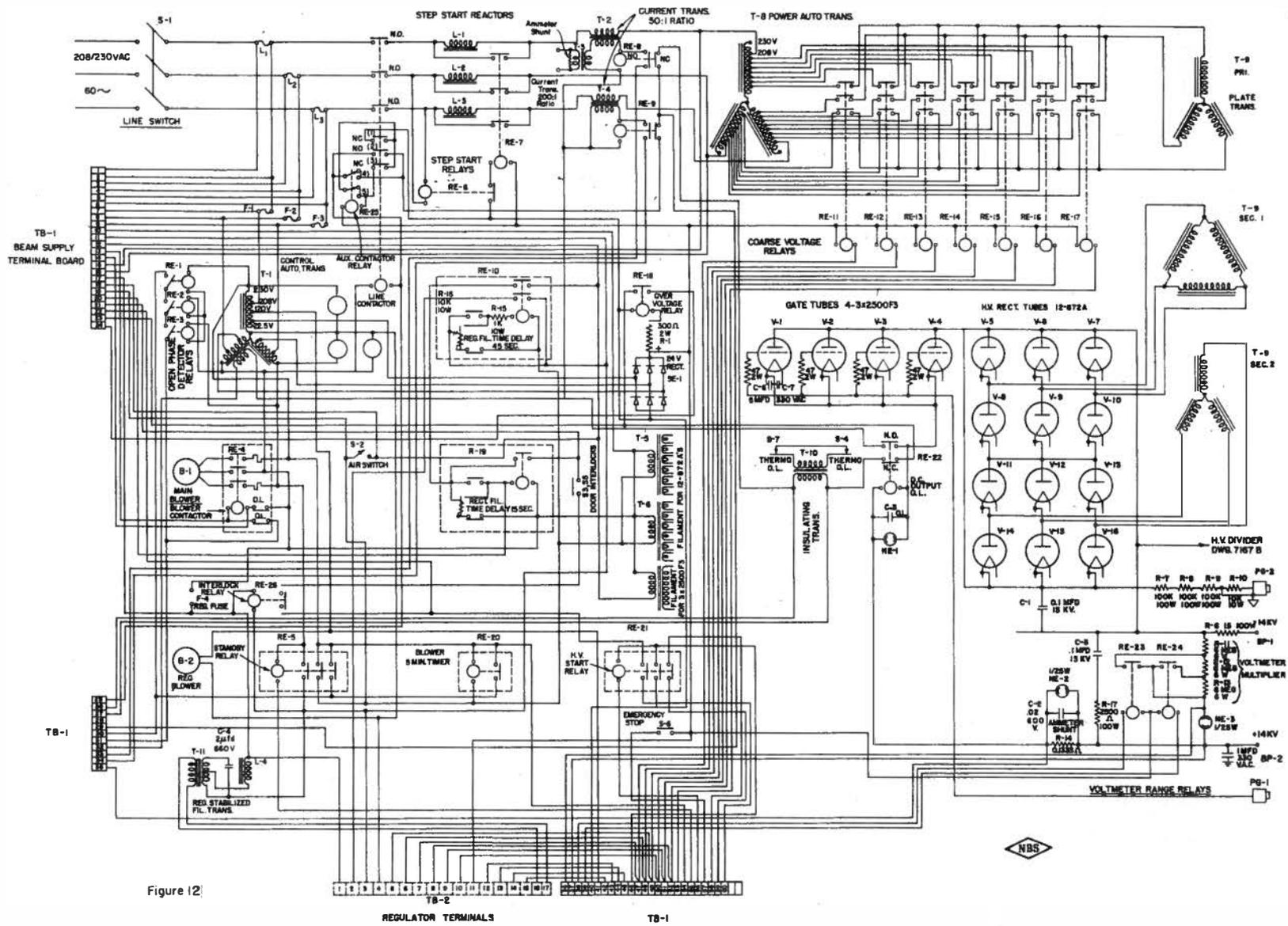


Figure 12

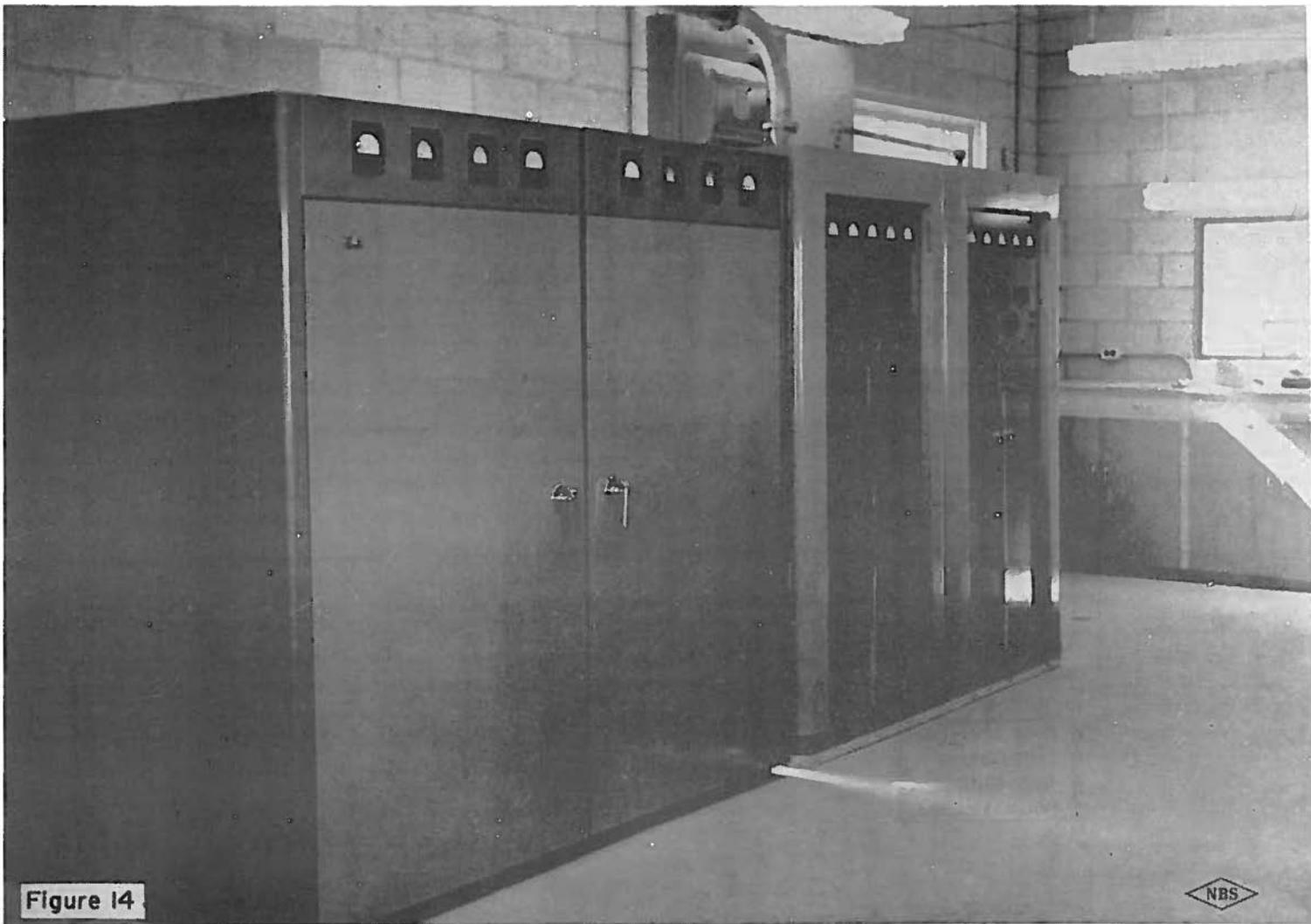


Figure 14

NBS

BLOCK DIAGRAM OF 1046.475 Mc RECORDING RECEIVER

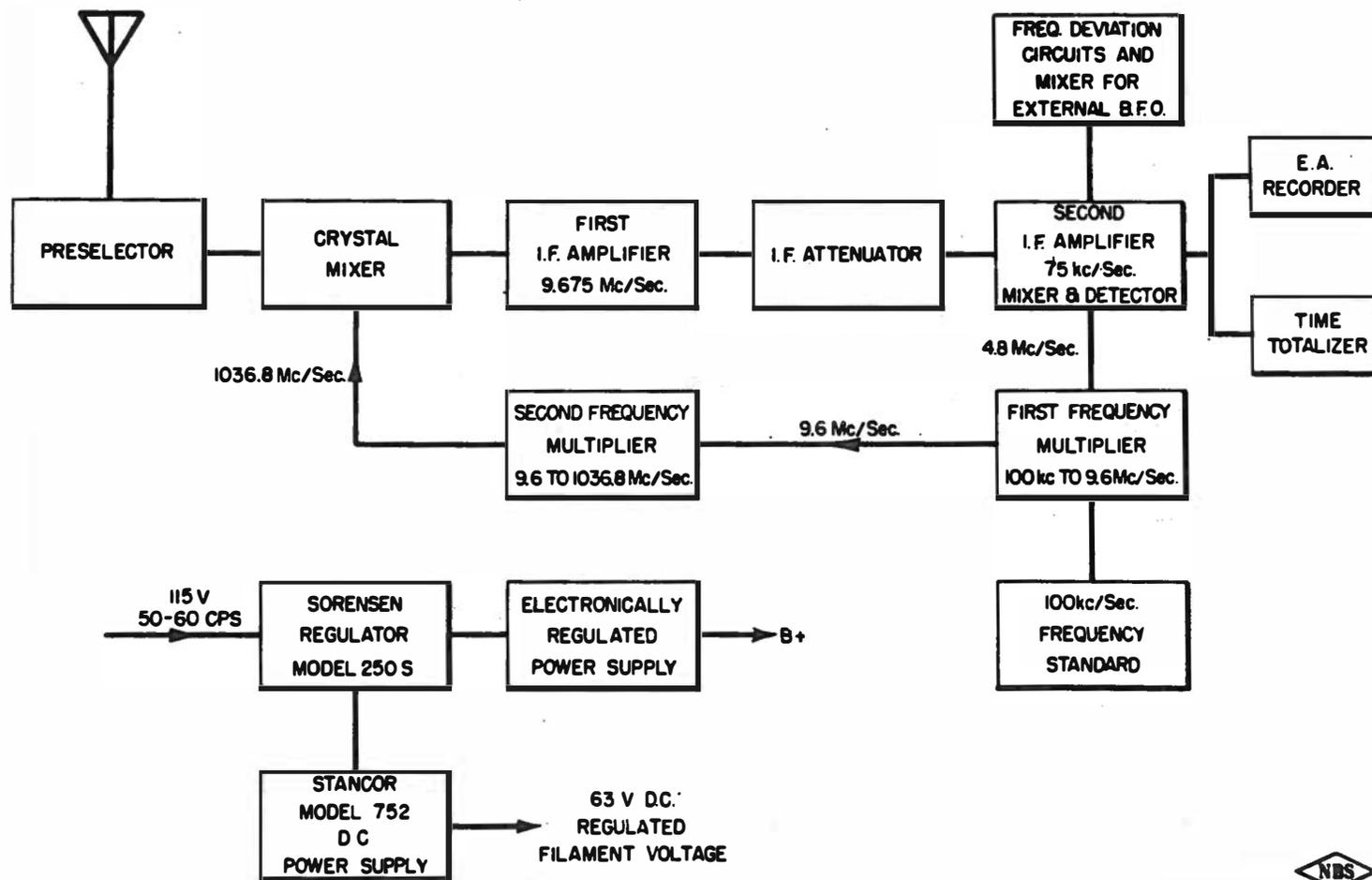
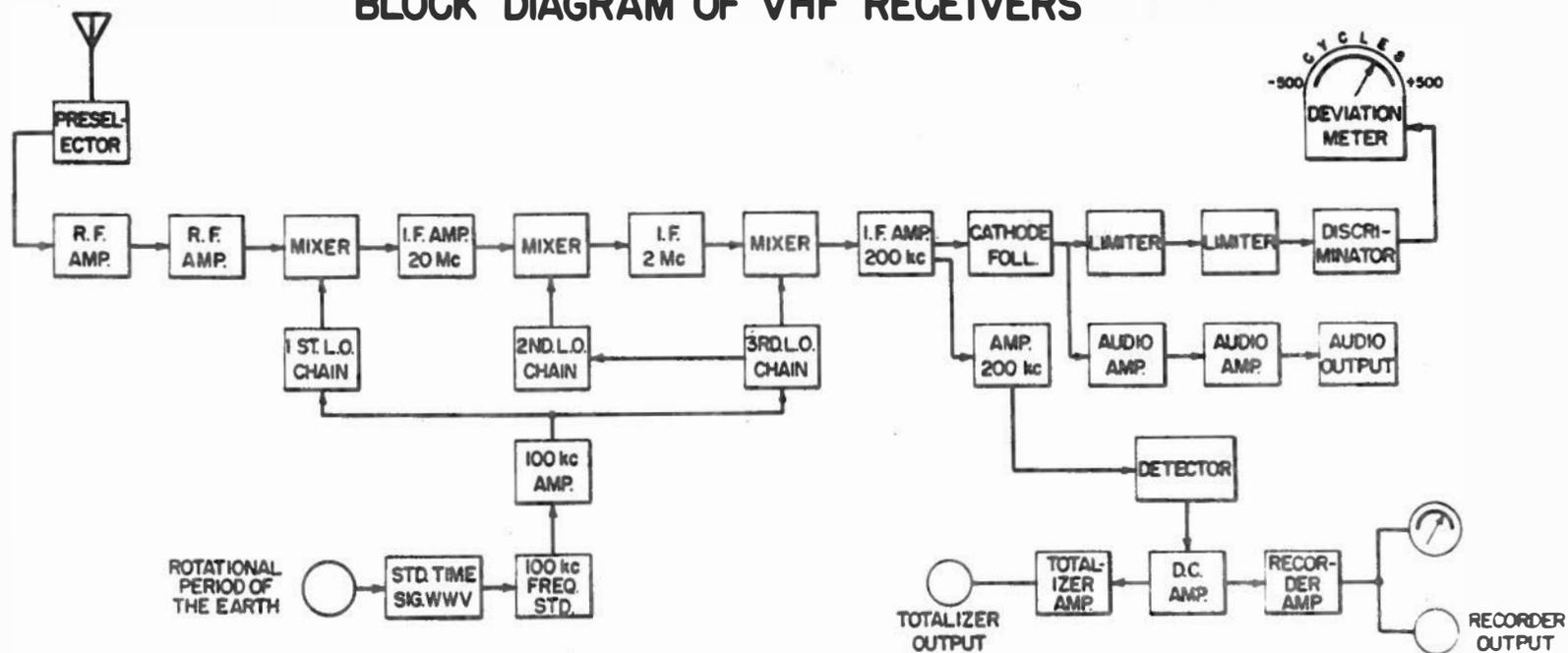


Figure 15



BLOCK DIAGRAM OF VHF RECEIVERS

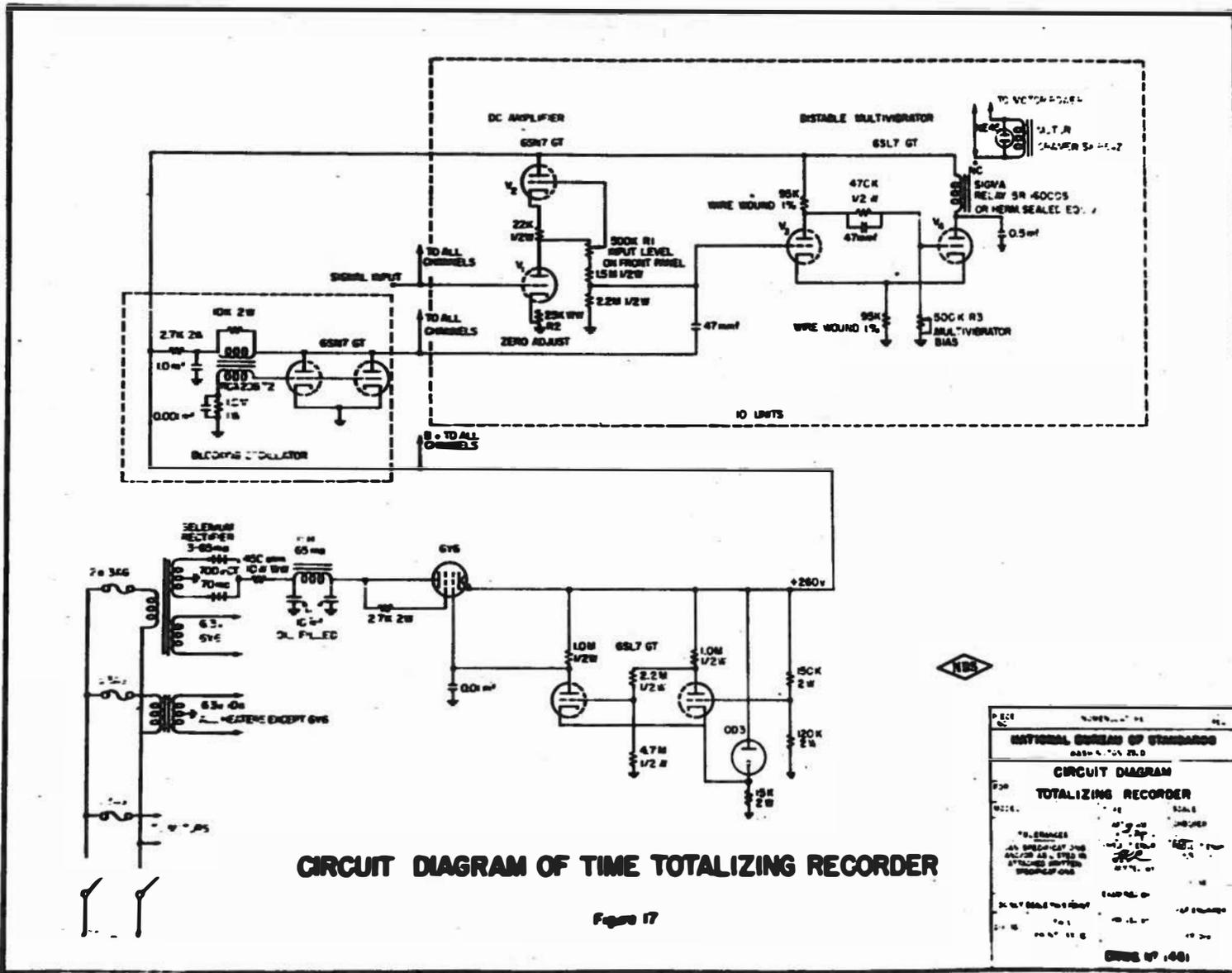


LOCAL OSCILLATOR FREQUENCIES (Mc)

| SIG. FREQ. | LOCAL OSC. | INPUT | MULT. FREQ. | OUTPUT |
|-----------------------|------------|-------|--|--------|
| 92 | 1 ST. | 0.1 | 0.1, 0.3, 0.9, 1.8, 9, 18, 36, 72 | 72 |
| 100 | 1 ST. | 0.1 | 0.1, 0.5, 2.5, 5, 15, 30, 60, 120 | 120 |
| 192.8 | 1 ST. | 0.1 | 0.1, 0.3, 0.9, 2.7, 5.4, 10.8, 21.6, 43.2, 86.4, 172.8 | 172.8 |
| 210.4 | 1 ST. | 0.1 | 0.1, 0.3, 0.9, 1.8, 3.6, 7.2, 14.4, 28.8, 57.6, 115.2, 230.4 | 230.4 |
| 92, 100, 192.8, 210.4 | 2 ND | 1.8 | 1.8, 9, 18 | 18 |
| | 3 RD | 0.1 | 0.1, 0.3, 0.9, 1.8 | 1.8 |



Figure 16



| | | | |
|------------------------------|-------|---|--------|
| P. 602 | | NUMBER OF PAGES | |
| NATIONAL BUREAU OF STANDARDS | | | |
| BUREAU OF STANDARDS | | | |
| CIRCUIT DIAGRAM | | | |
| TOTALIZING RECORDER | | | |
| DATE | SCALE | DESIGNED BY | INCHES |
| 1954 | 1/2" | J. H. ... | 1/2" |
| TOLERANCES | | UNLESS OTHERWISE SPECIFIED | |
| RESISTORS | | AS SPECIFIED AND UNLESS OTHERWISE SPECIFIED | |
| CAPACITORS | | AS SPECIFIED AND UNLESS OTHERWISE SPECIFIED | |
| DIMENSIONS | | AS SPECIFIED AND UNLESS OTHERWISE SPECIFIED | |
| MATERIALS | | AS SPECIFIED AND UNLESS OTHERWISE SPECIFIED | |
| FINISH | | AS SPECIFIED AND UNLESS OTHERWISE SPECIFIED | |
| DRAWN BY | | | |
| CHECKED BY | | | |
| APPROVED BY | | | |
| DATE | | | |
| CIRCUIT NO. 1481 | | | |

BLOCK DIAGRAM OF TYPICAL RECORDING SITE

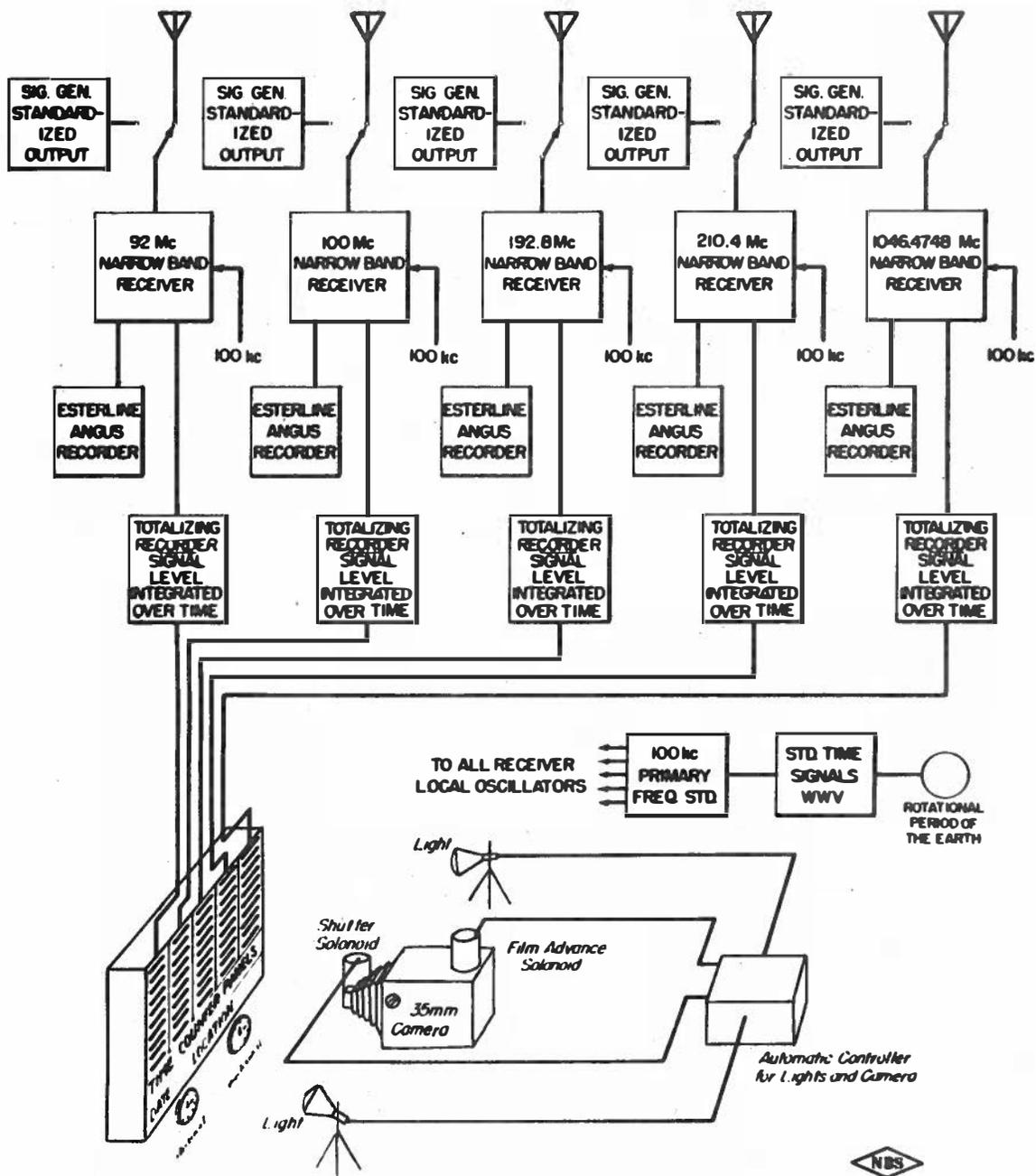
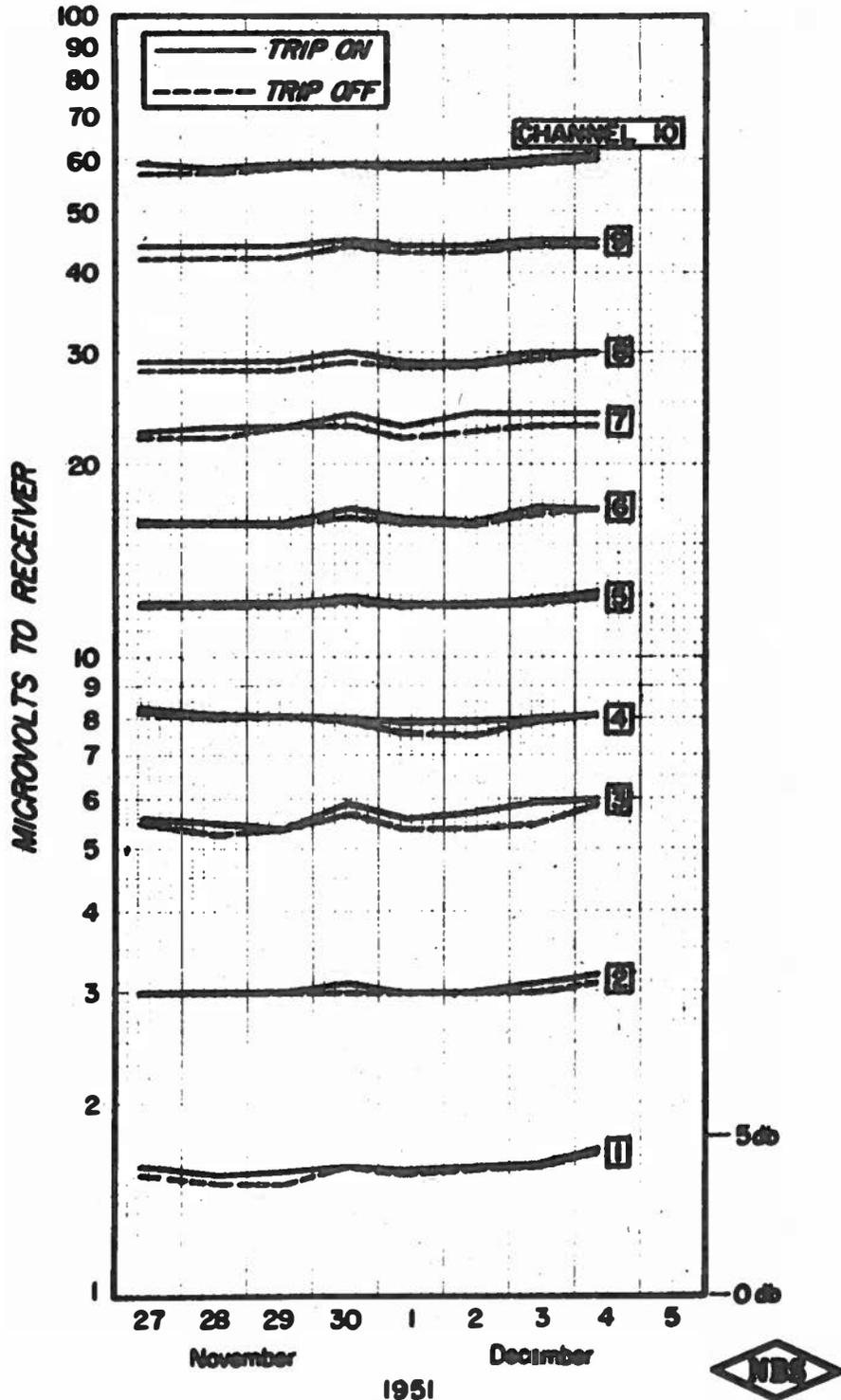


Figure 18

**CURVES SHOWING MEASURED STABILITY
OF RECEIVER-TOTALIZER SYSTEM FOR TYPICAL WEEK**

Dynamic Range of Receiver in 20 db Position



1951
Figure 19



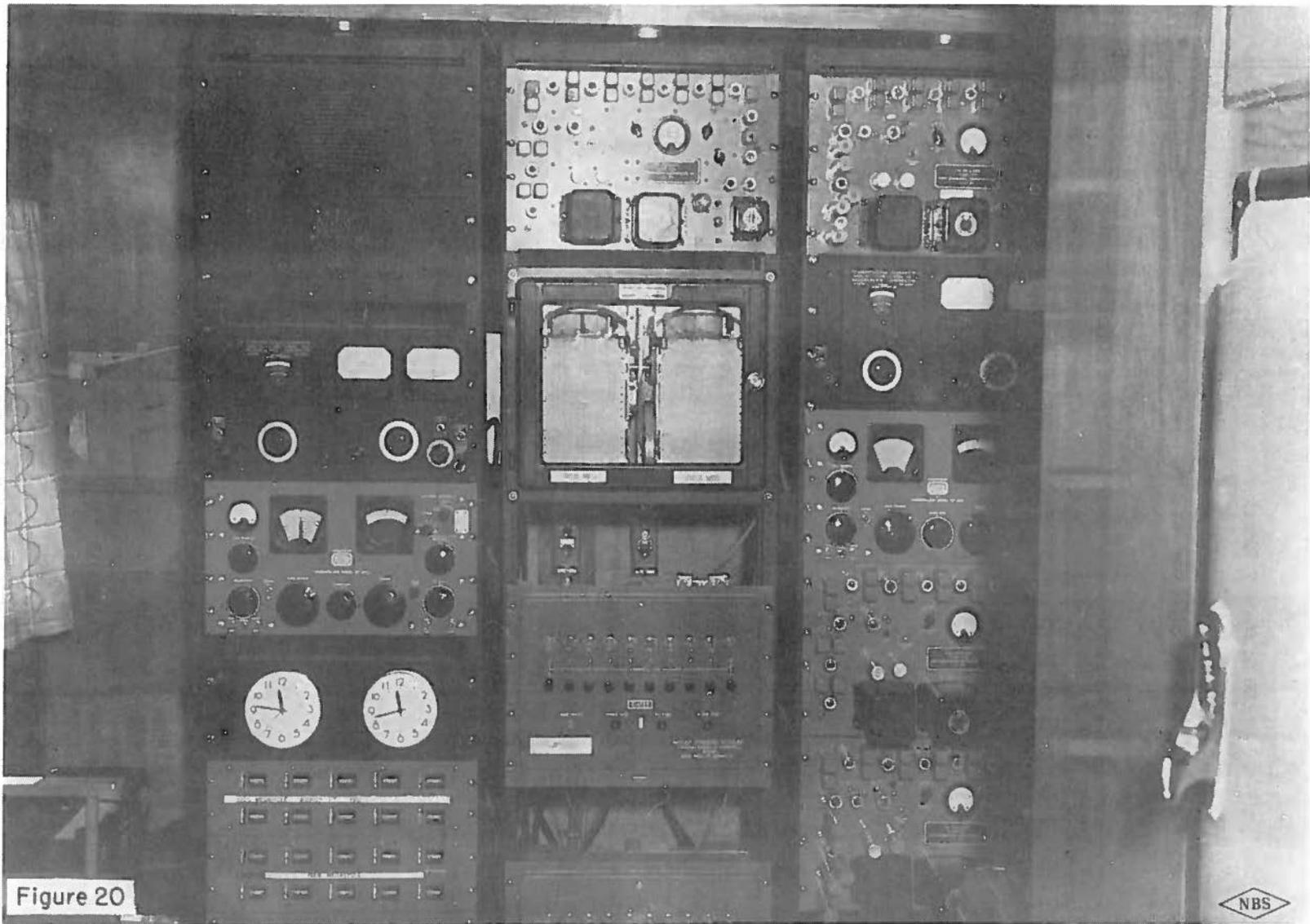


Figure 20

NBS

SAMPLE FAST SPEED RECORDINGS OF 92 MC AND 1046 MC TRANSMISSIONS FROM CHEYENNE MOUNTAIN

Distance 393.5 Miles

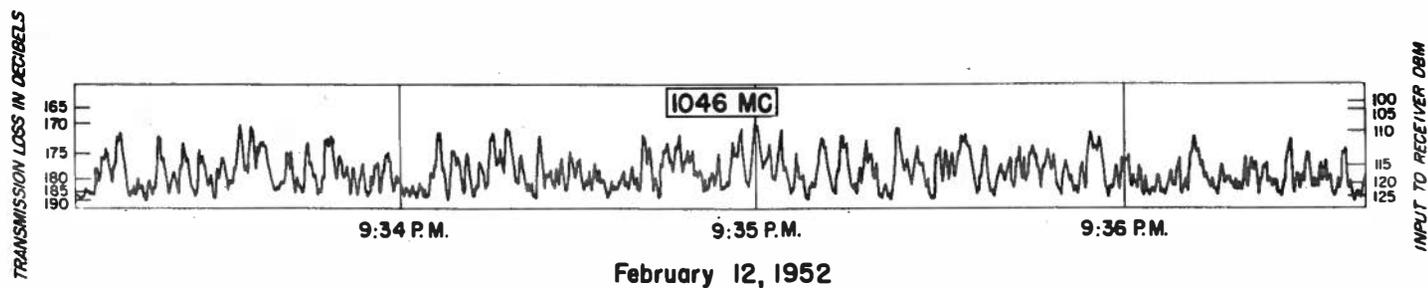
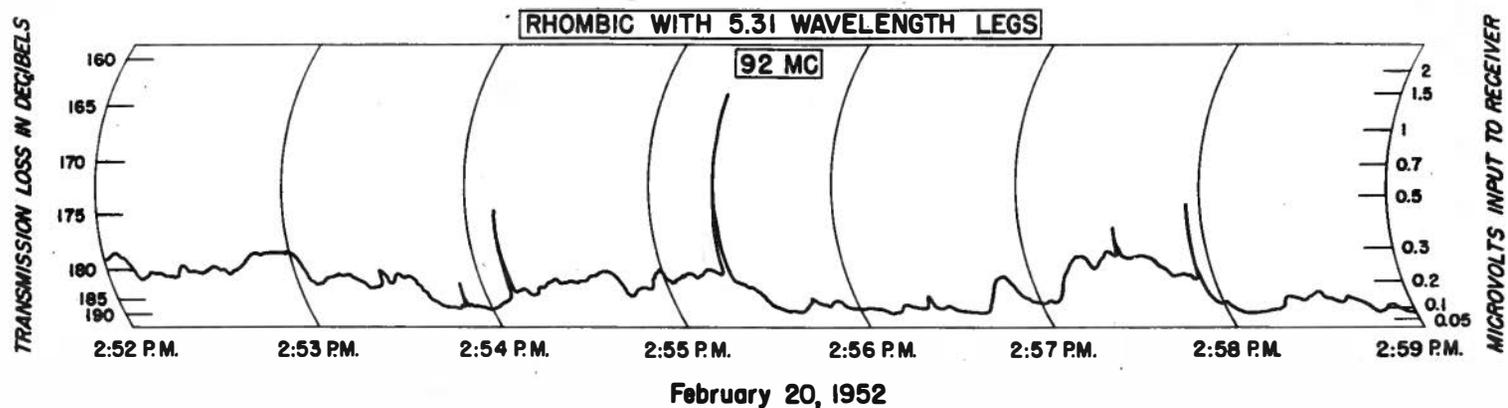


Figure 21

TRANSMISSION LOSS CHEYENNE MOUNTAIN TRANSMISSIONS

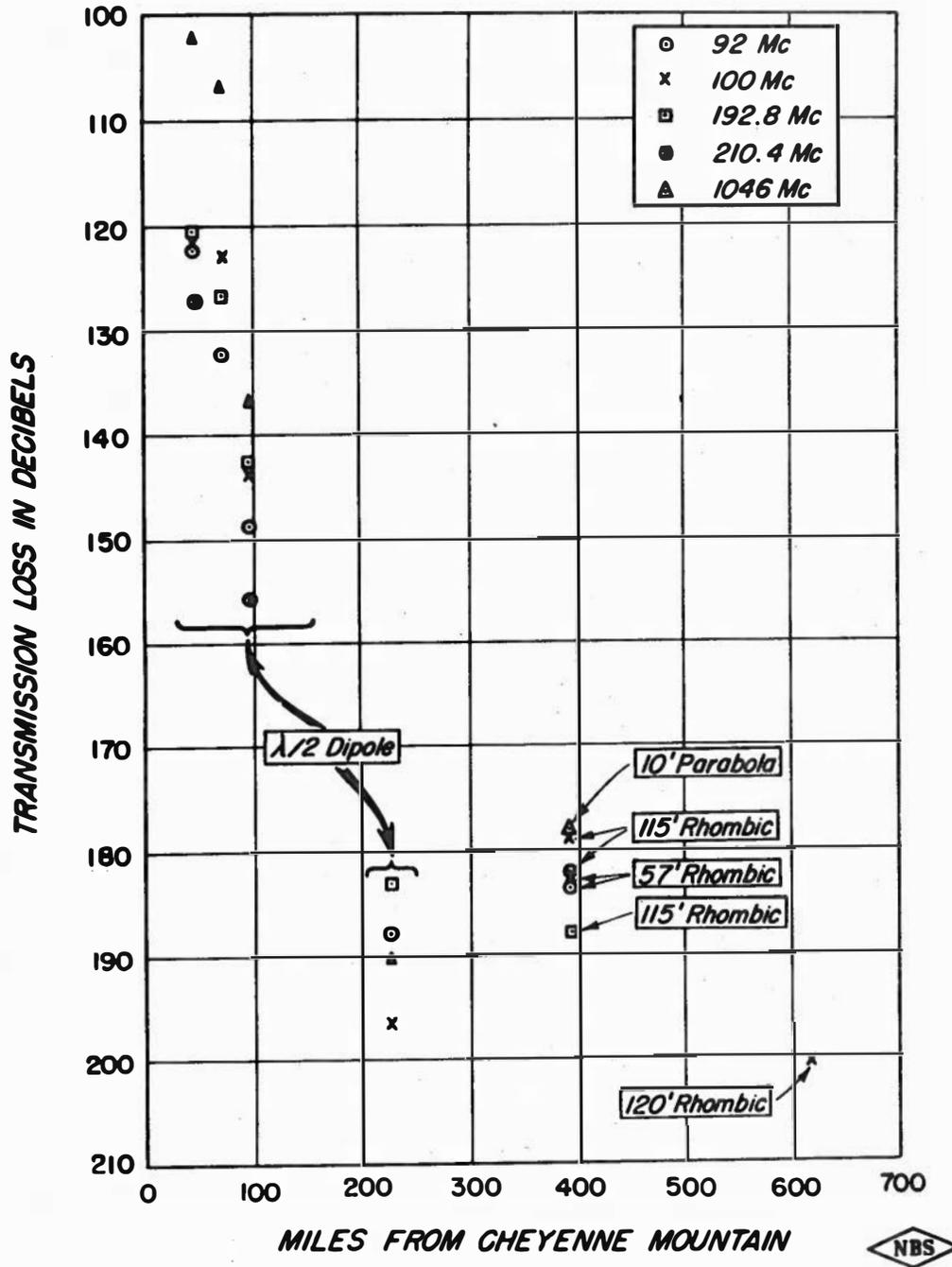


Figure 22

**TRANSMISSION ATTENUATION
RELATIVE TO FREE SPACE
CHEYENNE MOUNTAIN TRANSMISSIONS**

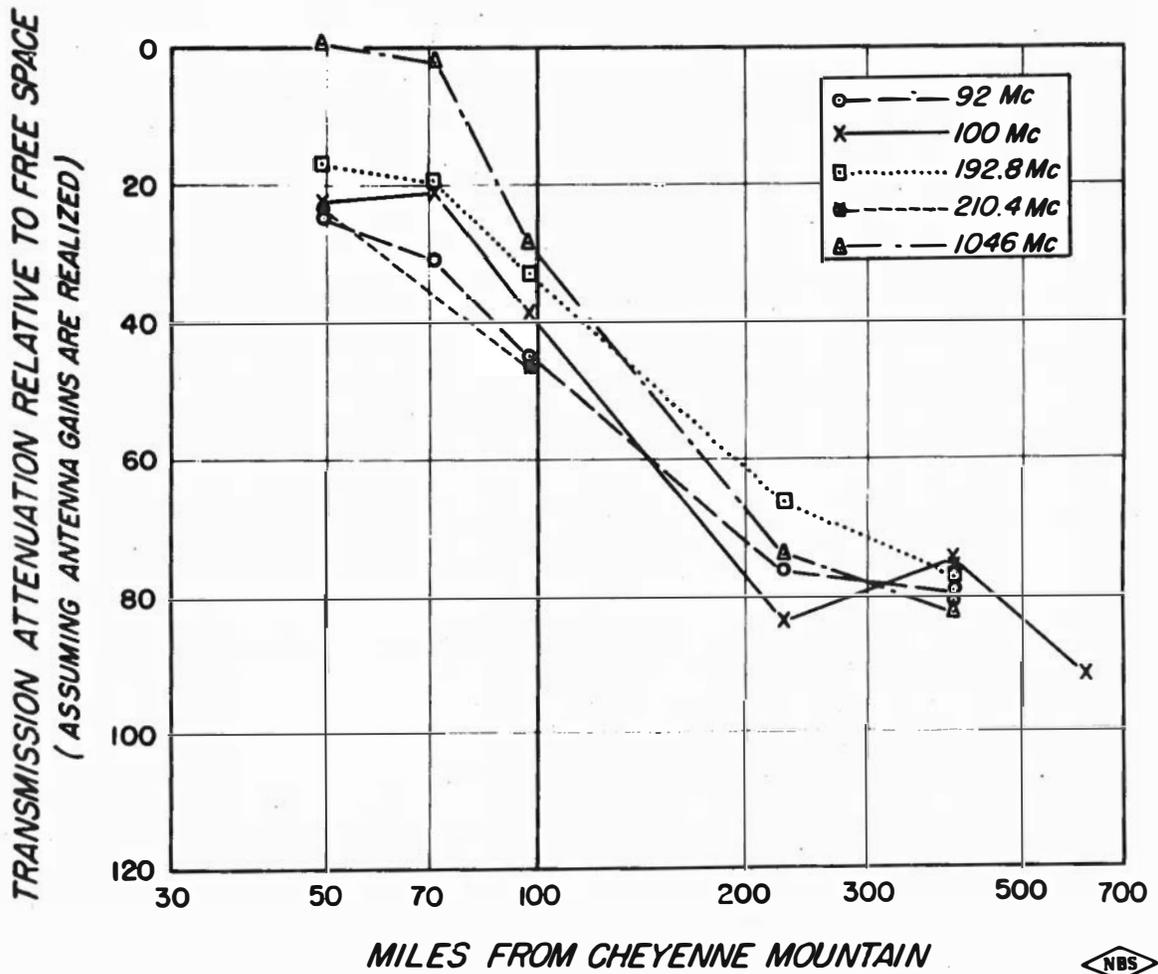


Figure 23

TRANSMISSION ATTENUATION RELATIVE TO FREE SPACE CHEYENNE MOUNTAIN TRANSMISSIONS

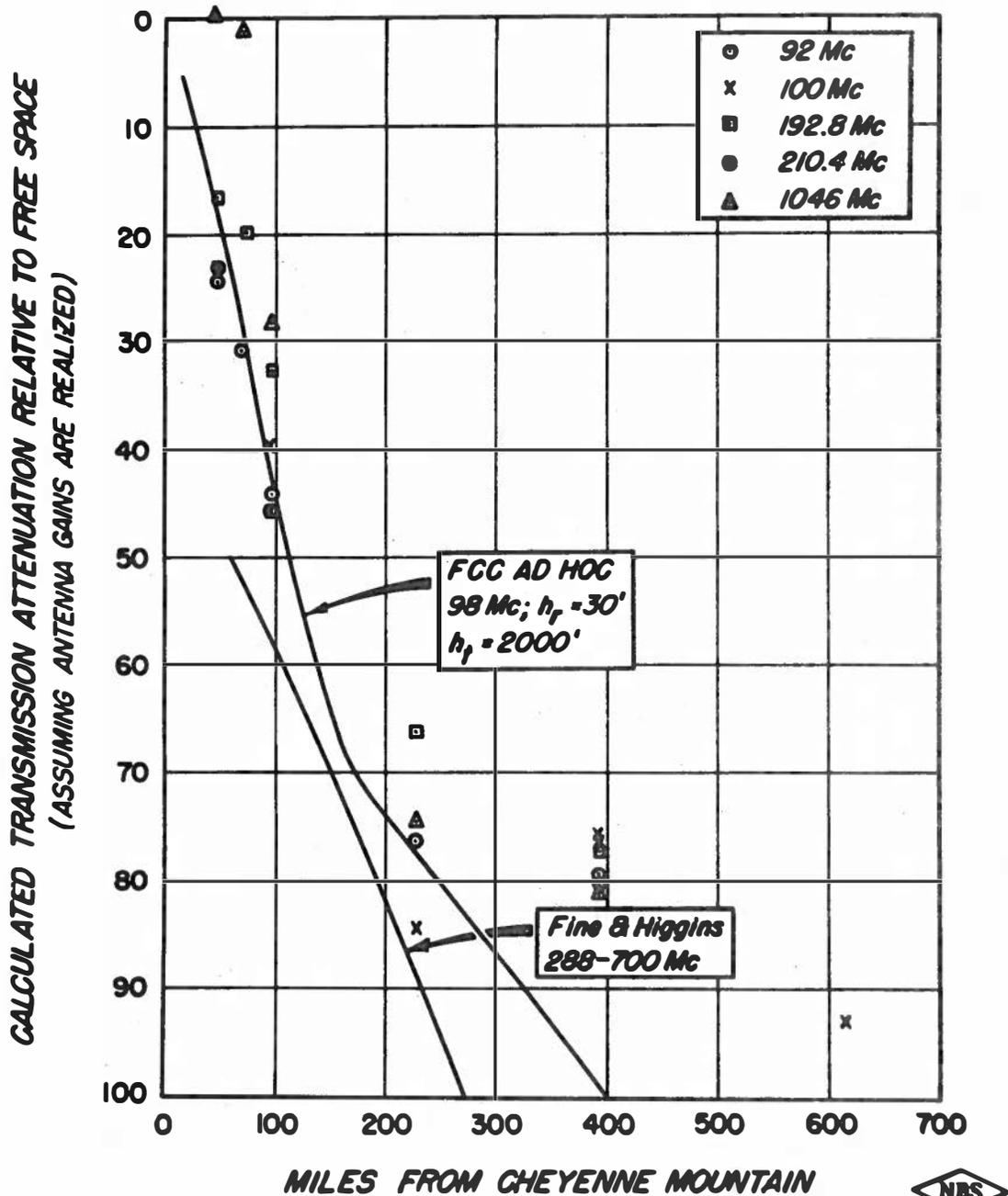


Figure 24

**TRANSMISSION ATTENUATION
RELATIVE TO FREE SPACE
CHEYENNE MOUNTAIN TRANSMISSIONS**

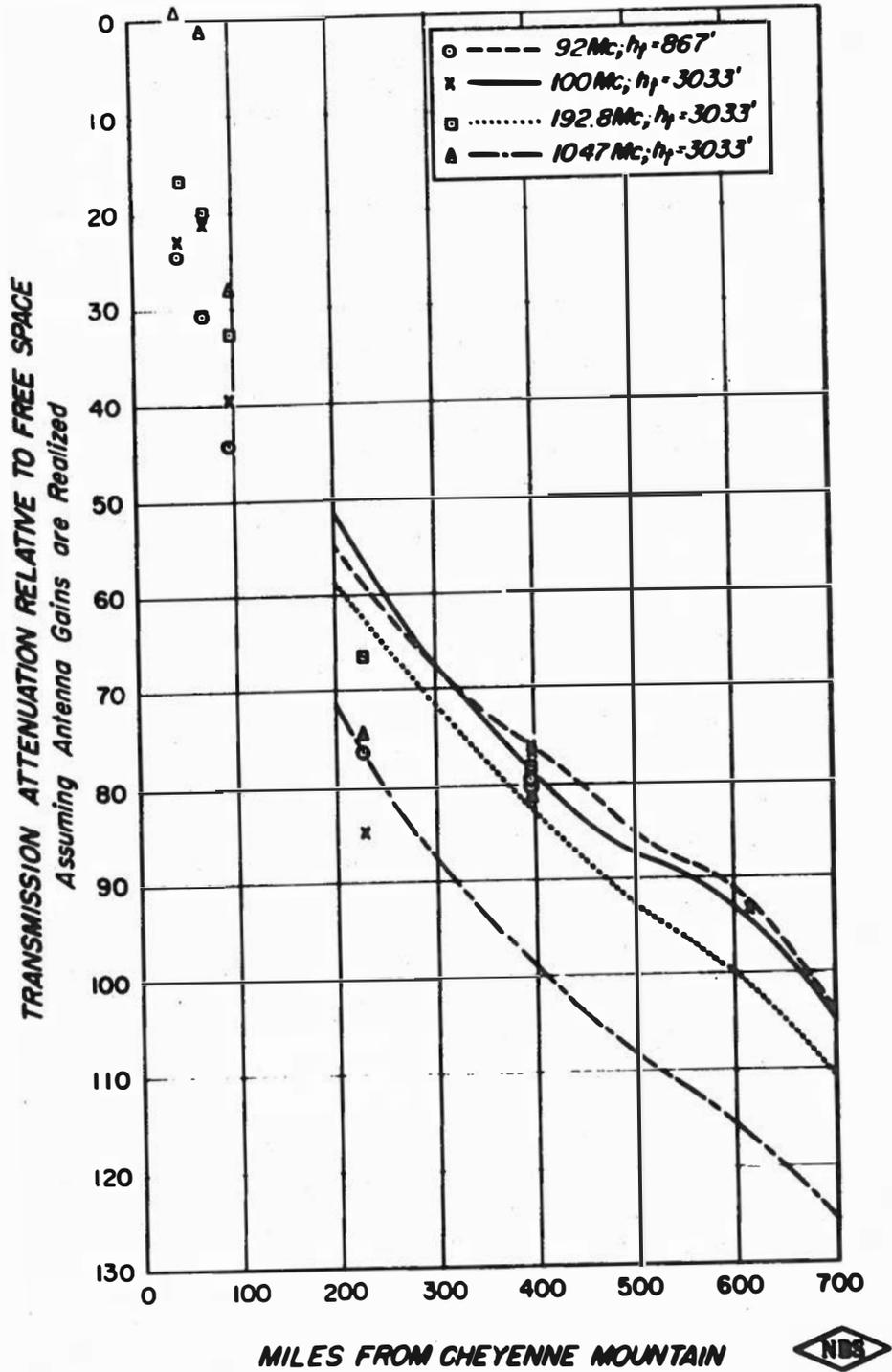


Figure 25

GEOMETRY OF TERRAIN INVOLVED IN PARTIAL TROPOSPHERIC REFLECTION THEORY

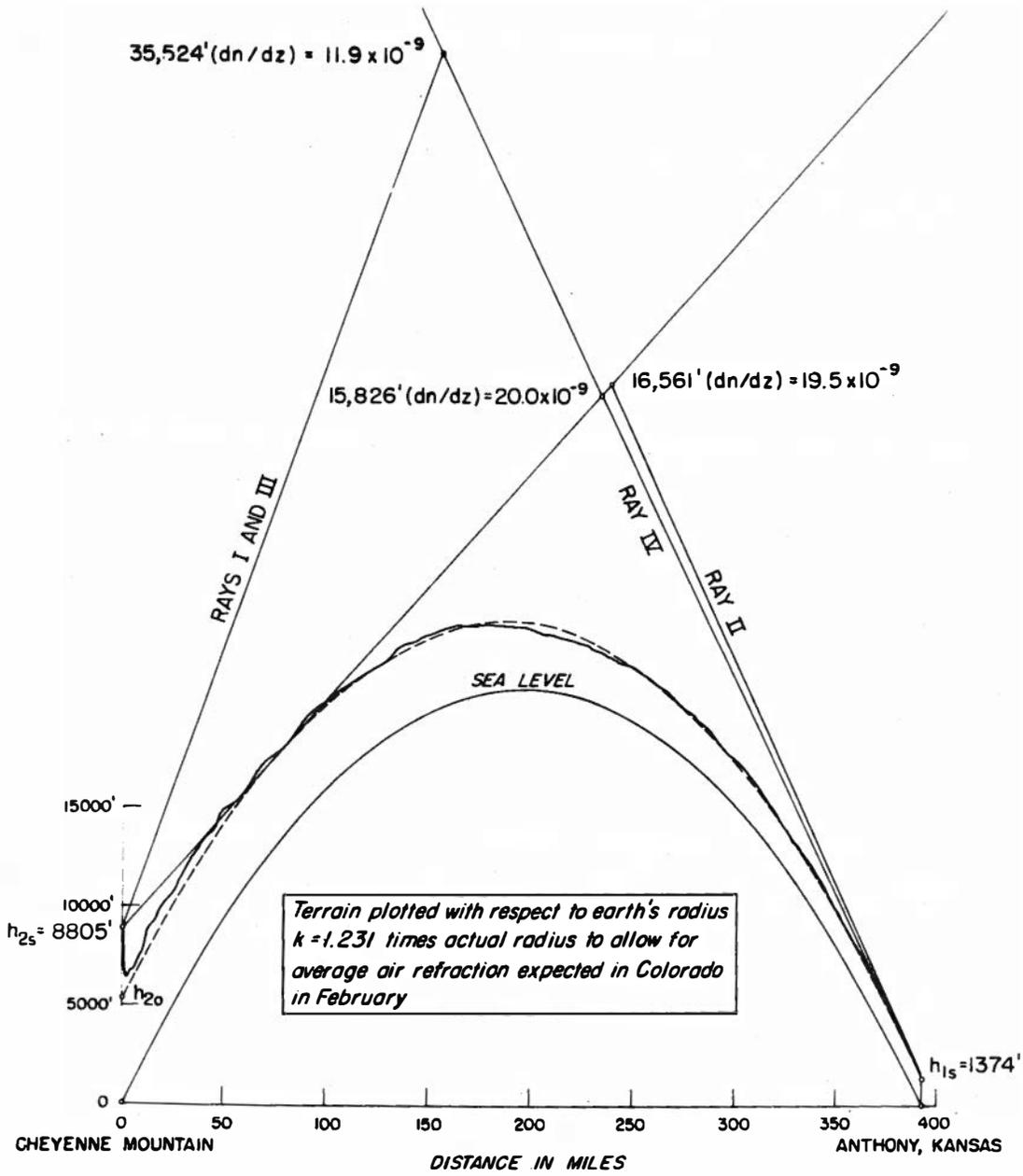


Figure 26

ILLUSTRATION OF RAY THEORY IN RADIO PROPAGATION

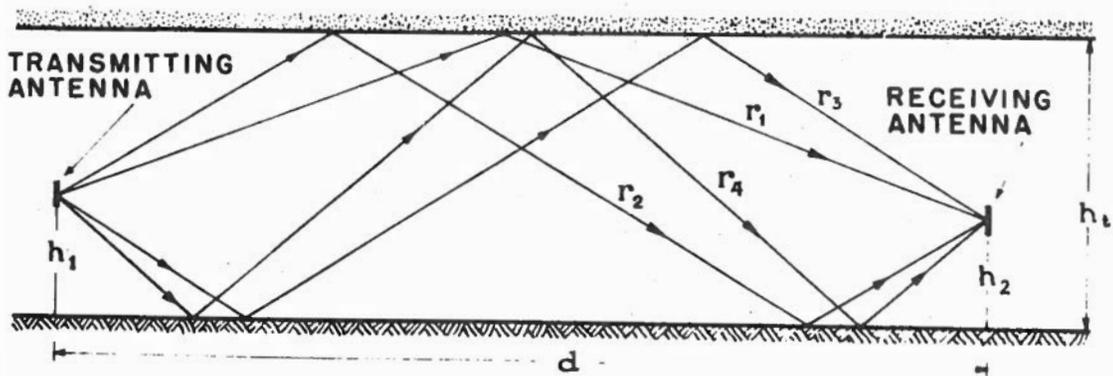
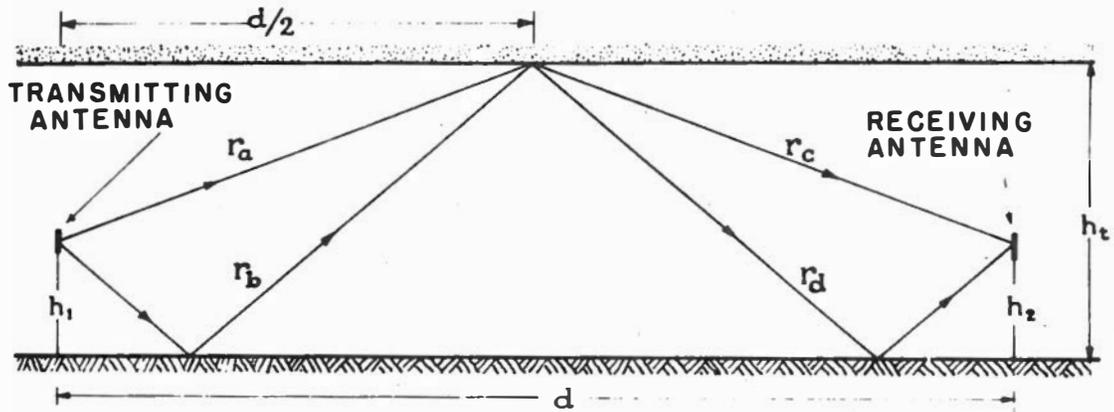


Figure 27



DISTRIBUTIONS OF INSTANTANEOUS SIGNAL LEVELS RECEIVED ON 100 MC AT 393.5 AND 616.3 MILES

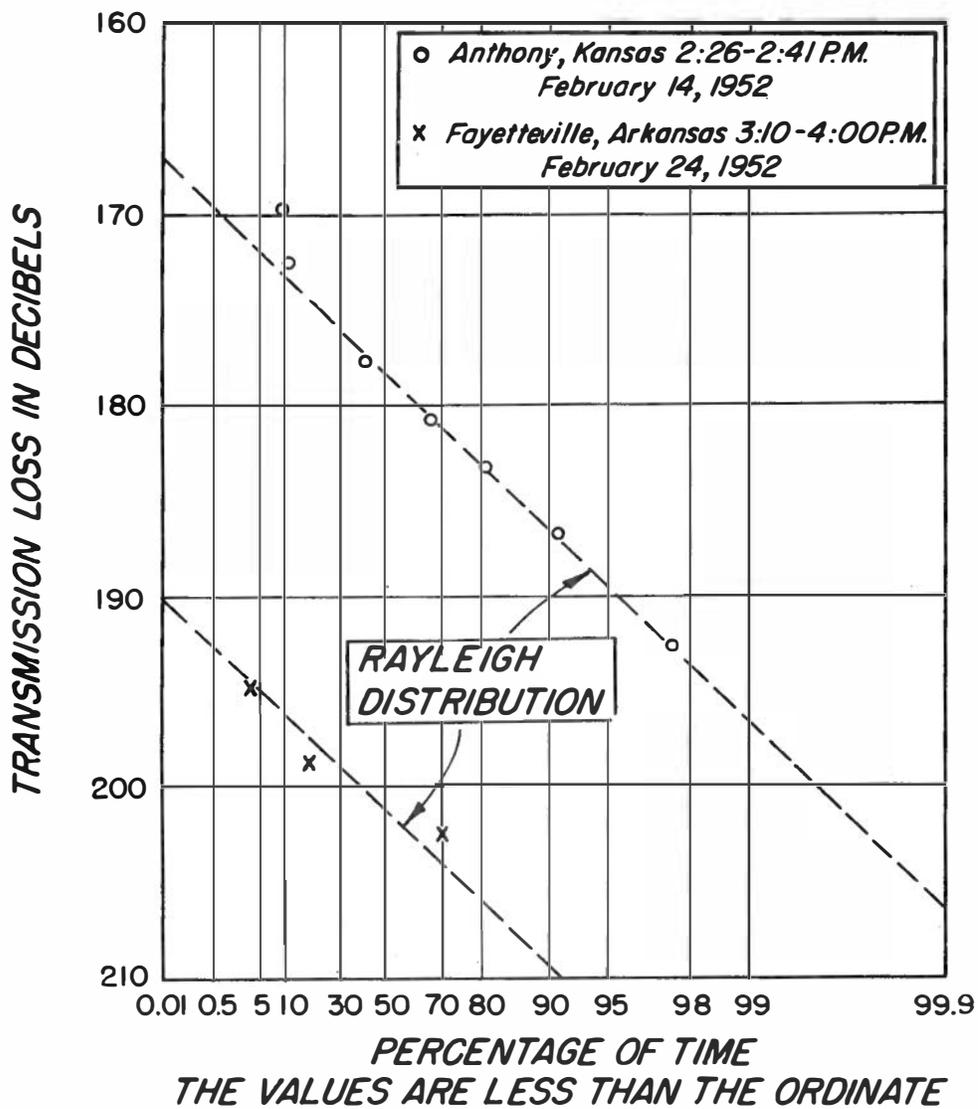


Figure 28

DISTRIBUTIONS OF HOURLY MEDIAN SIGNAL LEVELS
RECEIVED BETWEEN JANUARY 20 AND APRIL 1, 1952

100 Mc Transmitting Antenna $H_t = 5805 + 3000$ Feet; $G_t = 9.98$ db

1046 Mc Transmitting Antenna $H_t = 5805 + 2955$ Feet; $G_t = 26$ db

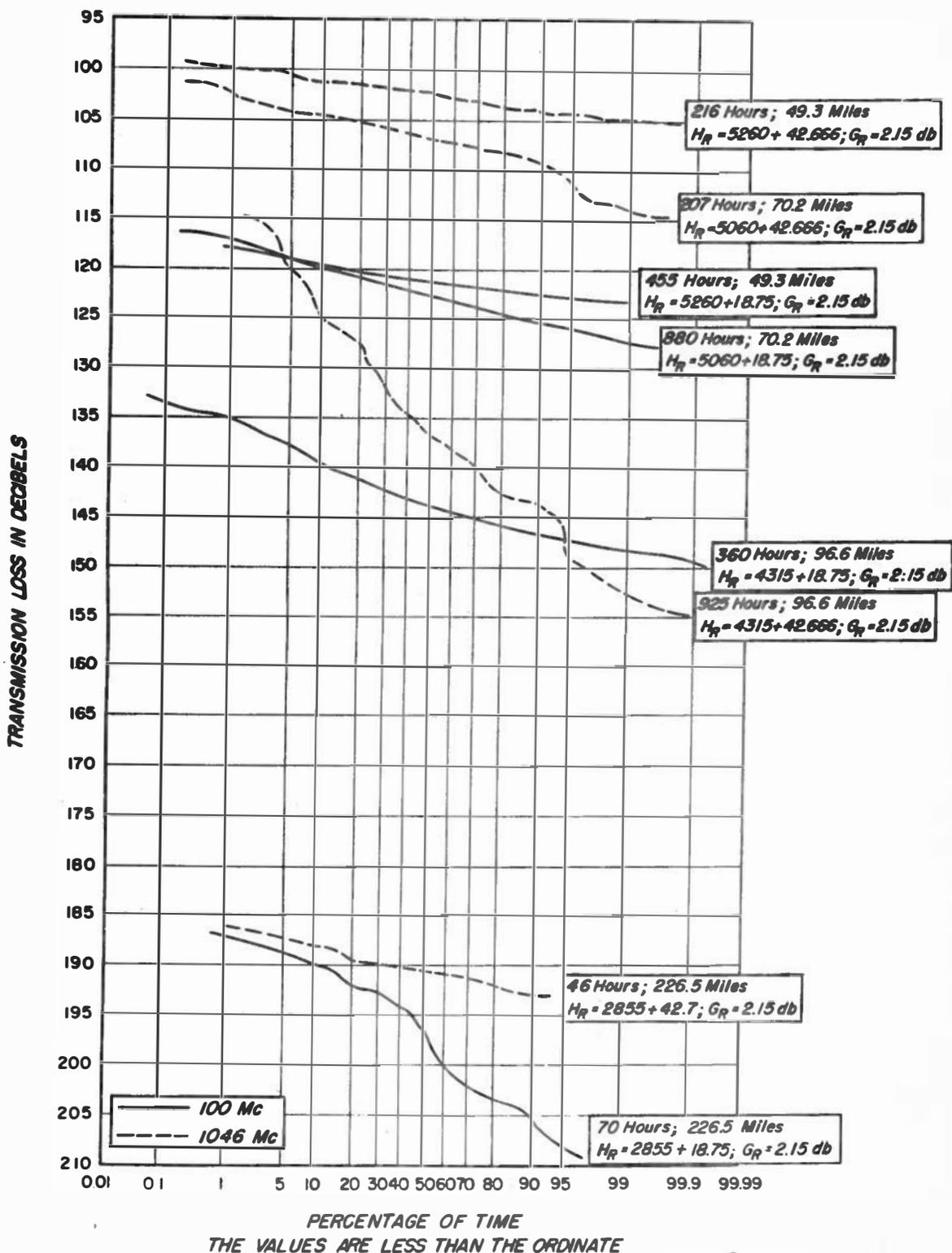


Figure 29



**DISTRIBUTIONS OF HOURLY MEDIAN SIGNAL LEVELS
RECEIVED BETWEEN JANUARY 20 AND APRIL 1, 1952**

92 Mc Transmitting Antenna $H_t = 5805 + 1680$ Feet; $G_t = 9.25$ db
 192.8 Mc Transmitting Antenna $H_t = 5805 + 3050$ Feet; $G_t = 10.40$ db
 210.4 Mc Transmitting Antenna $H_t = 5805 + 1700$ Feet; $G_t = 10.60$ db

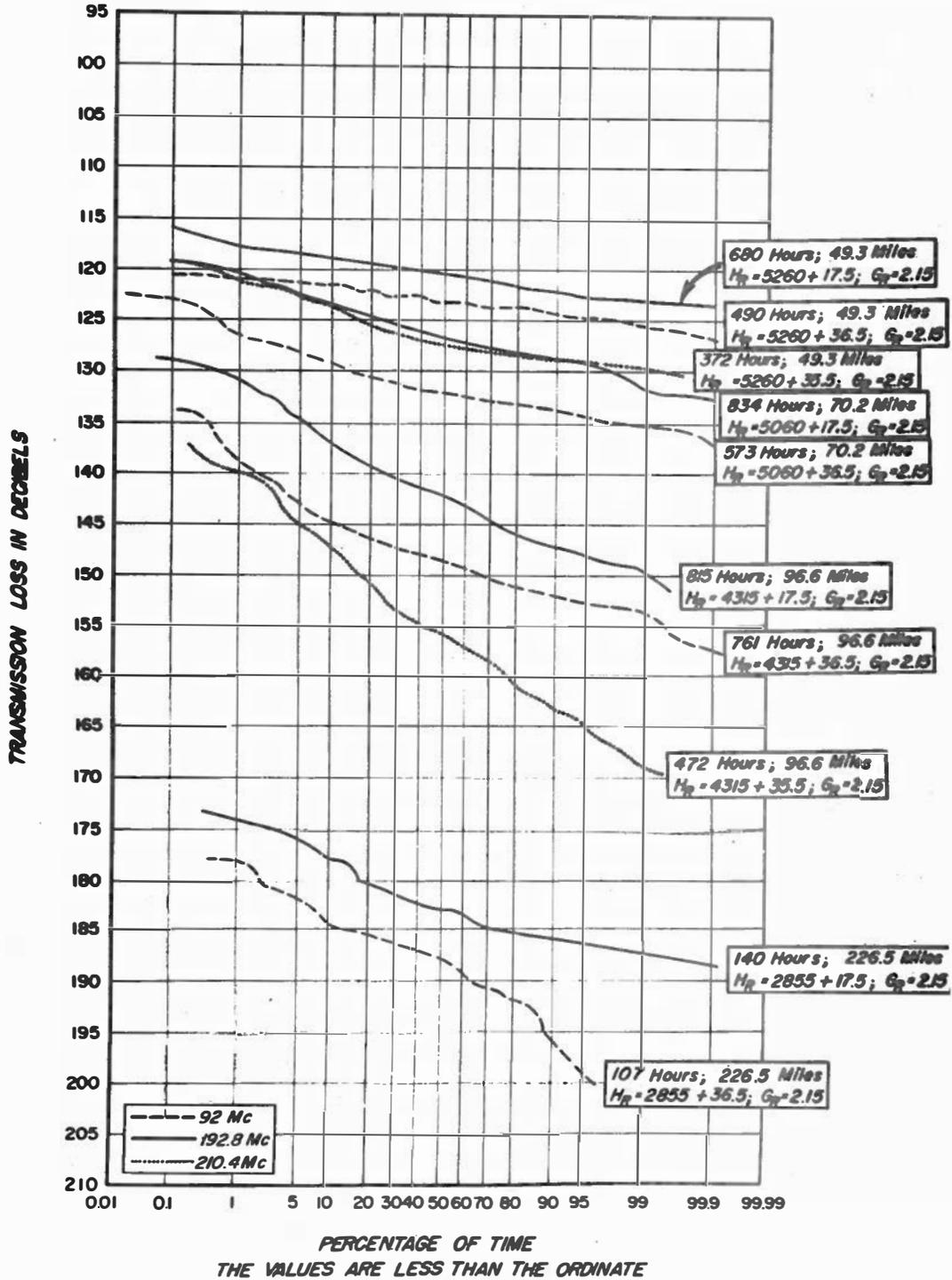


Figure 30



DIURNAL VARIATION OF SIGNAL LEVEL MEDIANS
BY 3 HOUR PERIODS

RECEIVED BETWEEN JANUARY 20, AND APRIL 1, 1952

100 Mc Transmitting Antenna Height 5805 + 3000 Feet Gain 9.98 Decibels

1046 Mc Transmitting Antenna Height 5805 + 2955 Feet Gain 26 Decibels

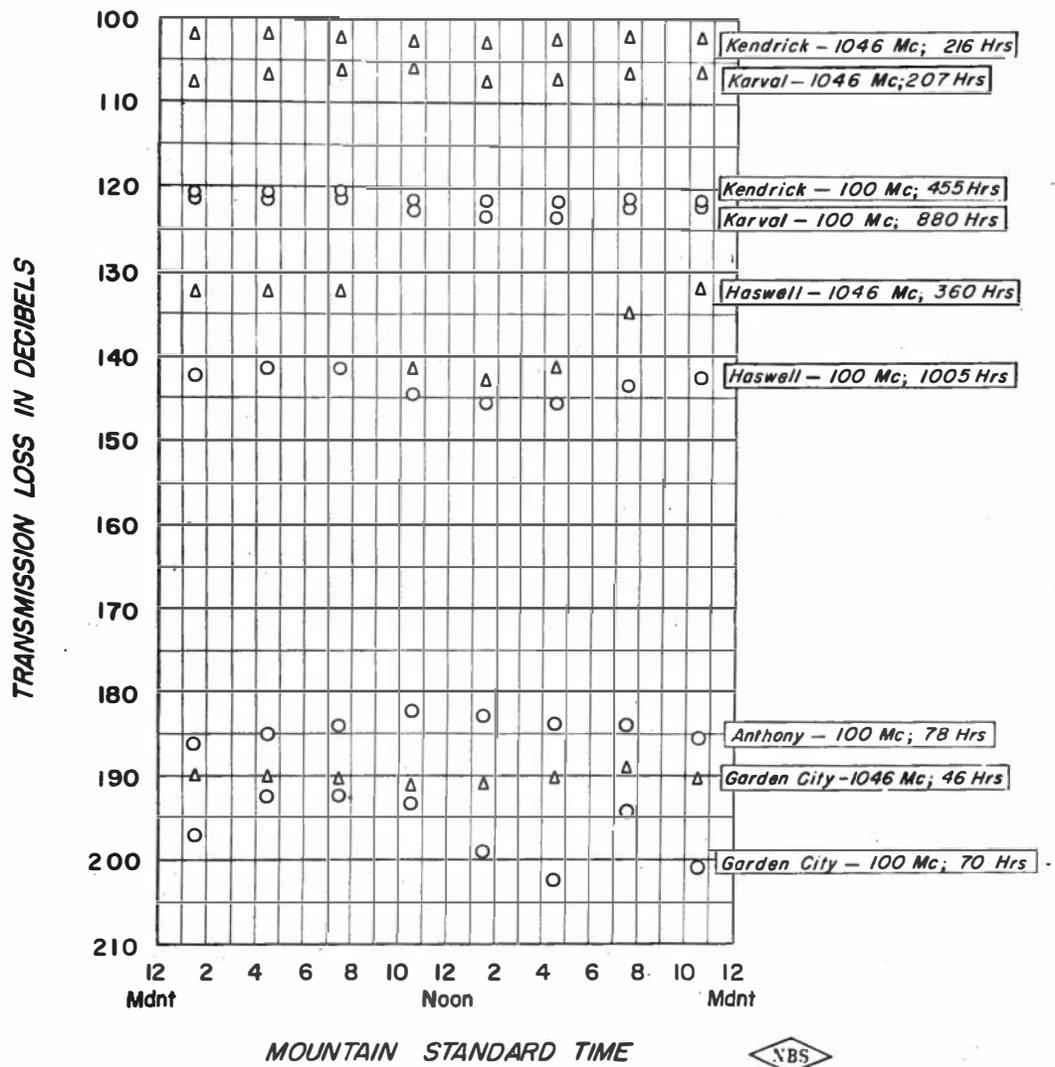


Figure 31.

**DIURNAL VARIATION OF HOURLY MEDIAN
FIELDS RECEIVED ON 100 MC AT ANTHONY, KANSAS**
Distance 393.5 Miles

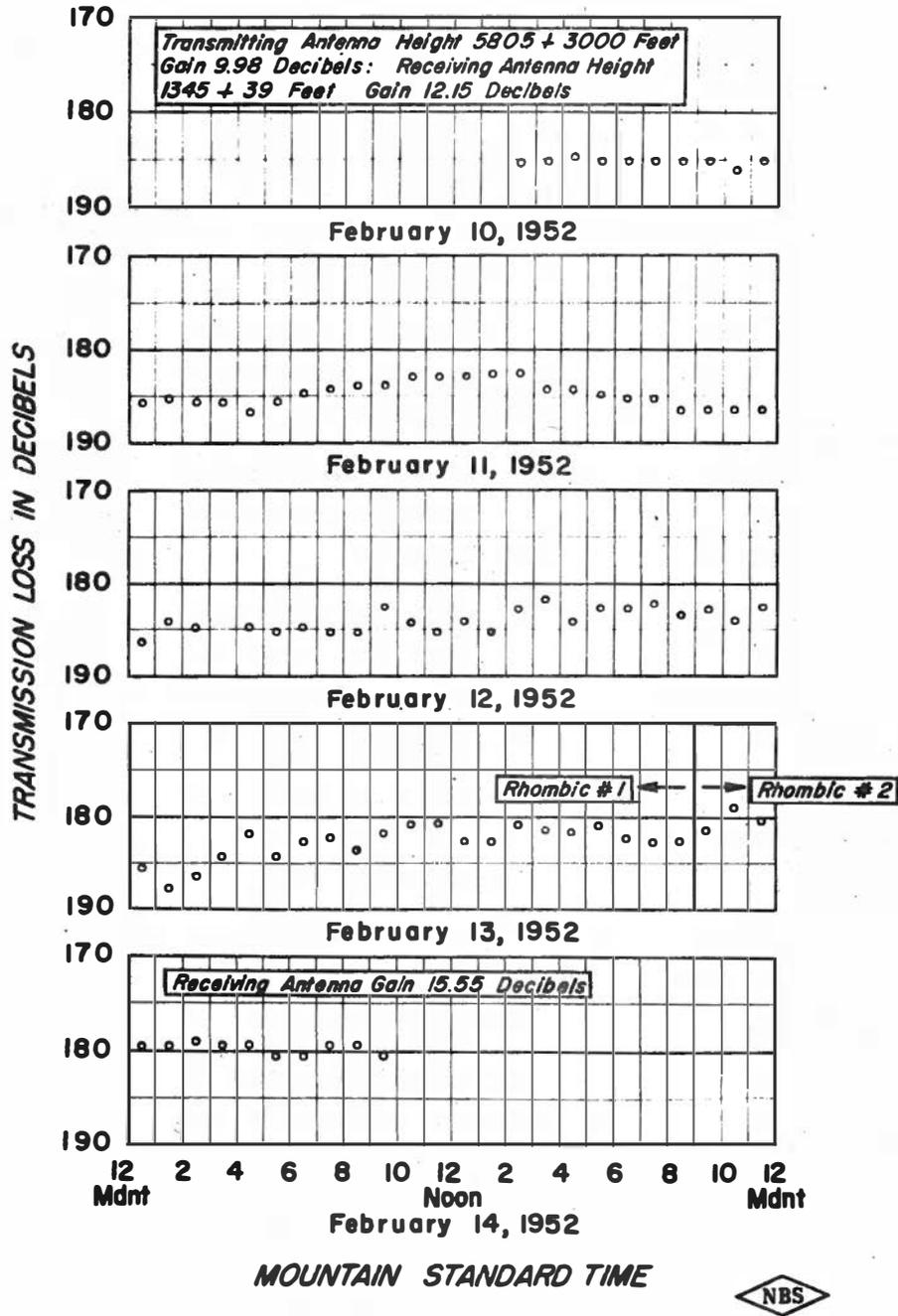


Figure 32

**SAMPLE RECORDINGS OF 100 MC TRANSMISSIONS
FROM CHEYENNE MOUNTAIN
Distance 616.3 Miles**

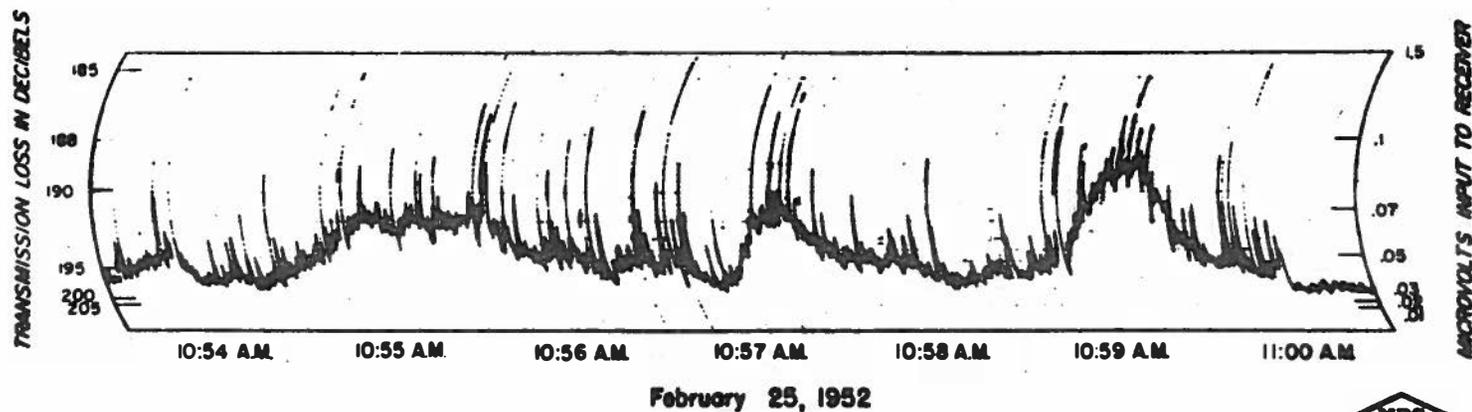
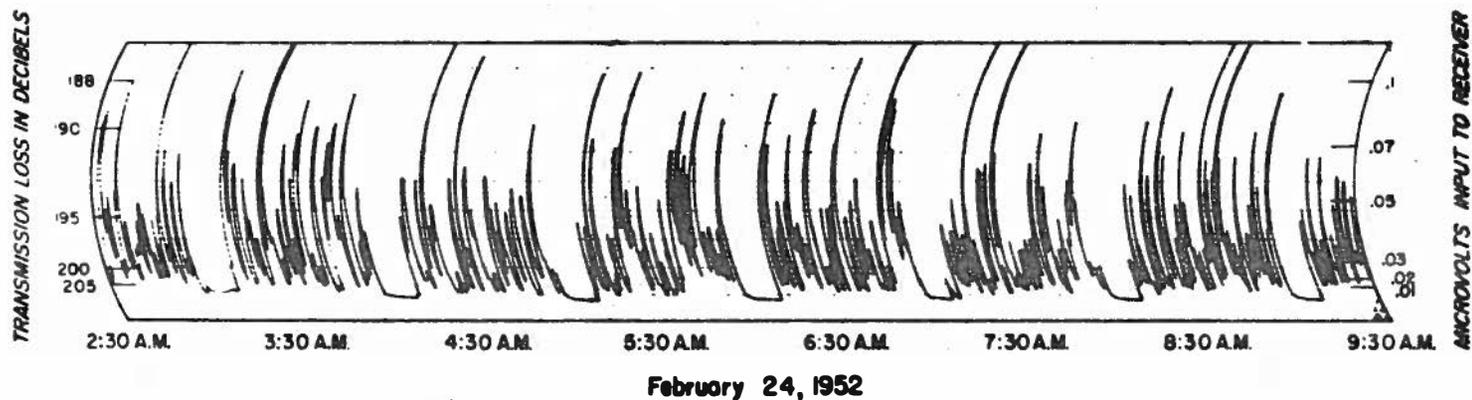


Figure 38

AVERAGE REFRACTIVE INDEX GRADIENT OVER CHEYENNE MOUNTAIN PATH

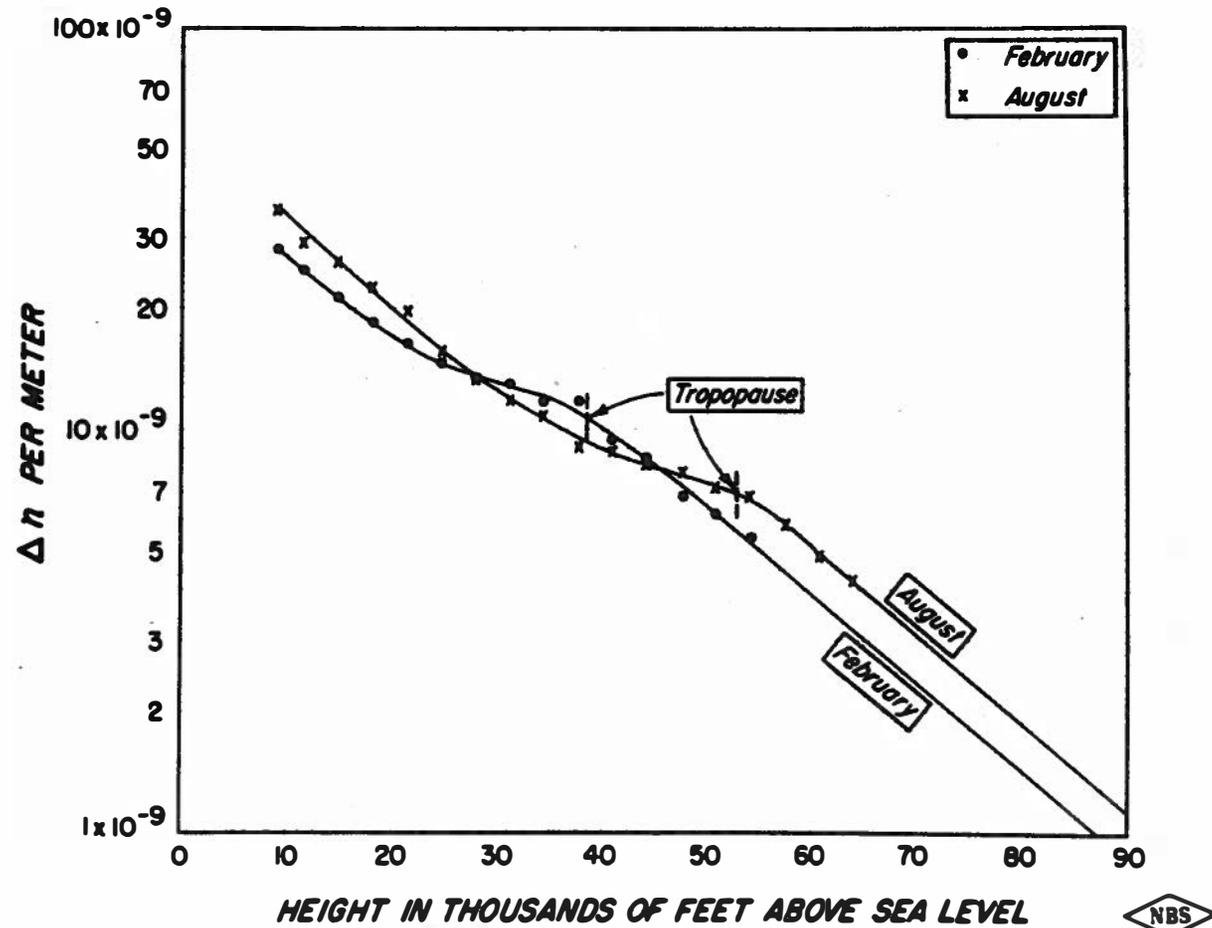


Figure 34



AVERAGE REFRACTIVE INDEX GRADIENT

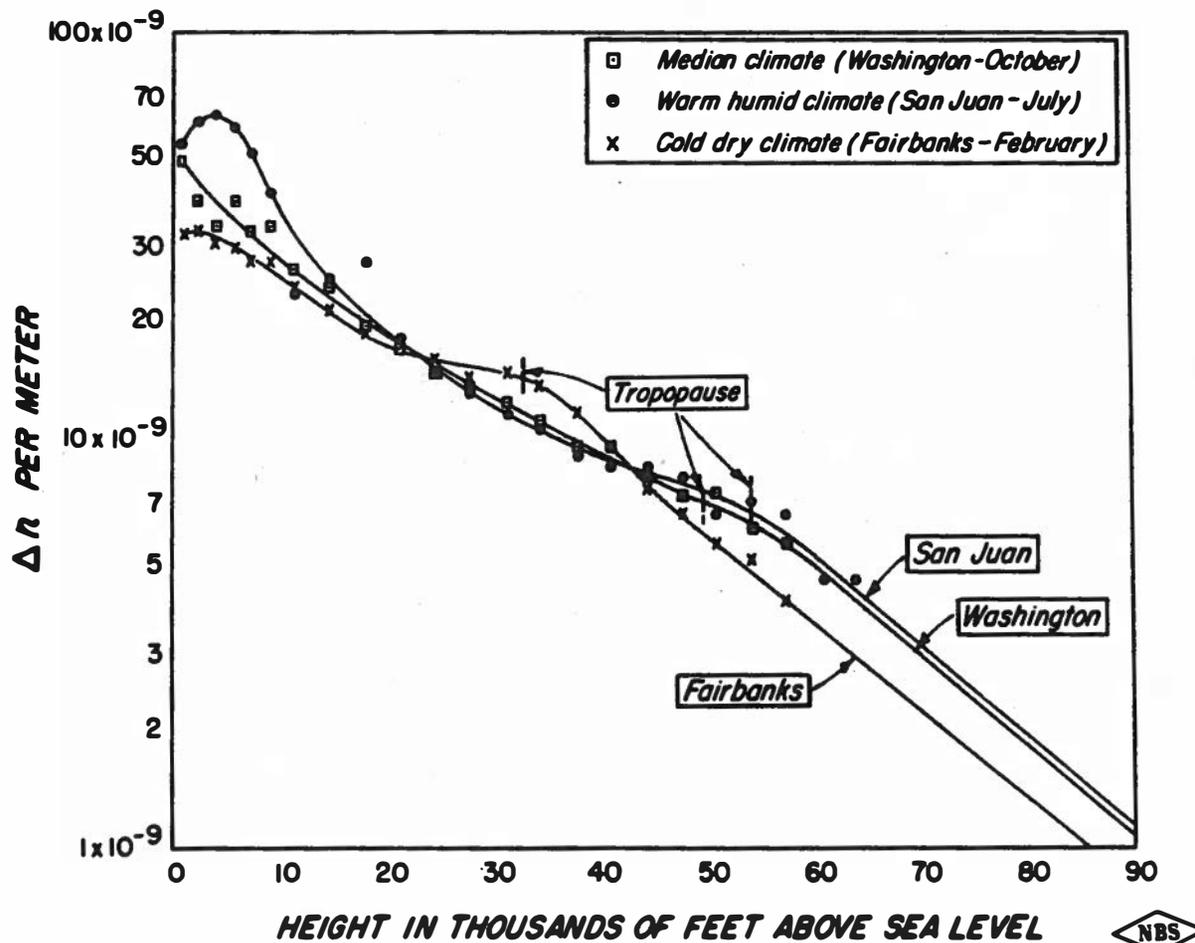


Figure 35

SIMULTANEOUS RECORDINGS OF 92 MC TRANSMISSIONS FROM CHEYENNE MOUNTAIN

Received On Rhombic Antennas Displaced Horizontally 50 Feet Normal To The Path
Distance 393.5 Miles

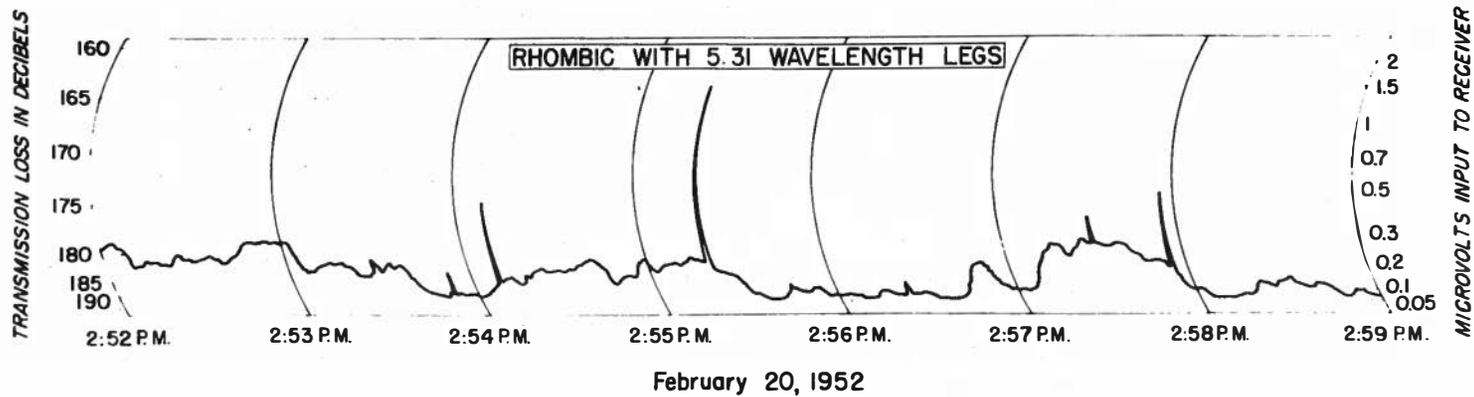
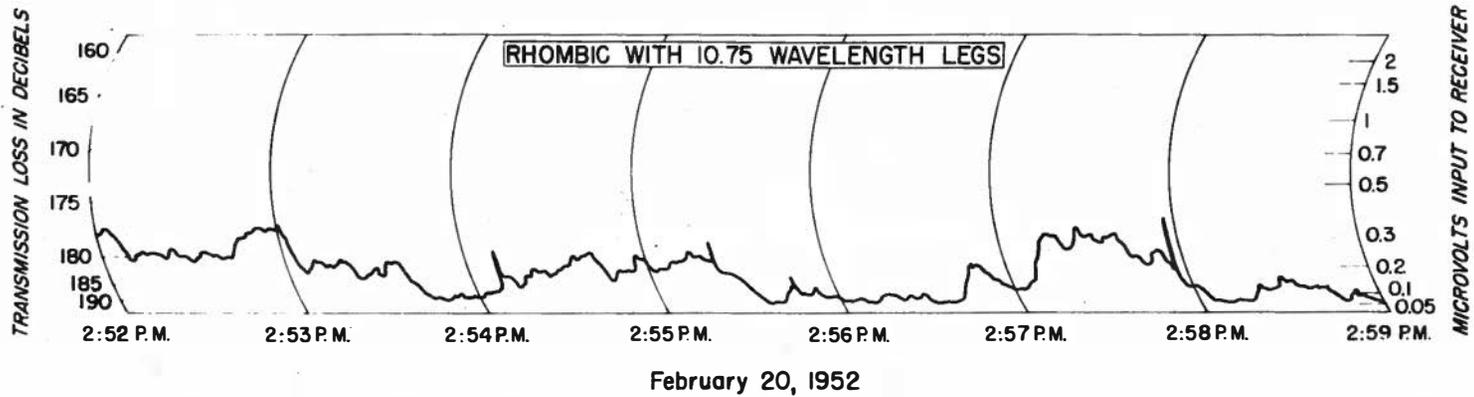


Figure 36



**SIMULTANEOUS RECORDINGS 92 MC AND 100 MC TRANSMISSIONS
FROM CHEYENNE MOUNTAIN
Distance 393.5 Miles**

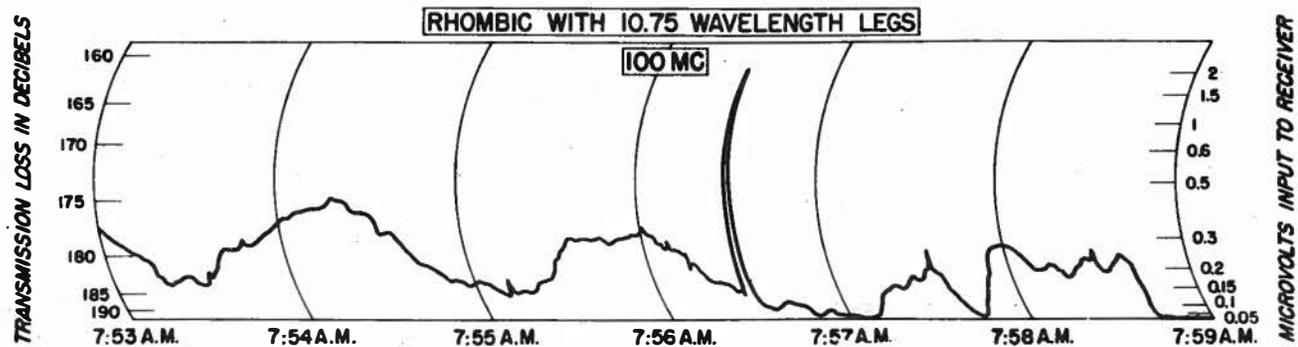
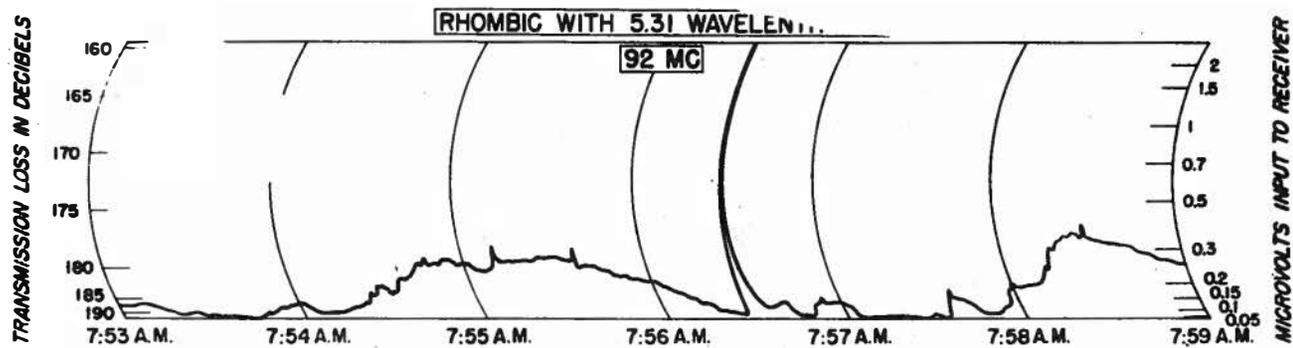


Figure 37



GEOMETRY ILLUSTRATING THE REGIONS WITHIN AND BEYOND THE "SPACE WAVE LINE OF SIGHT"

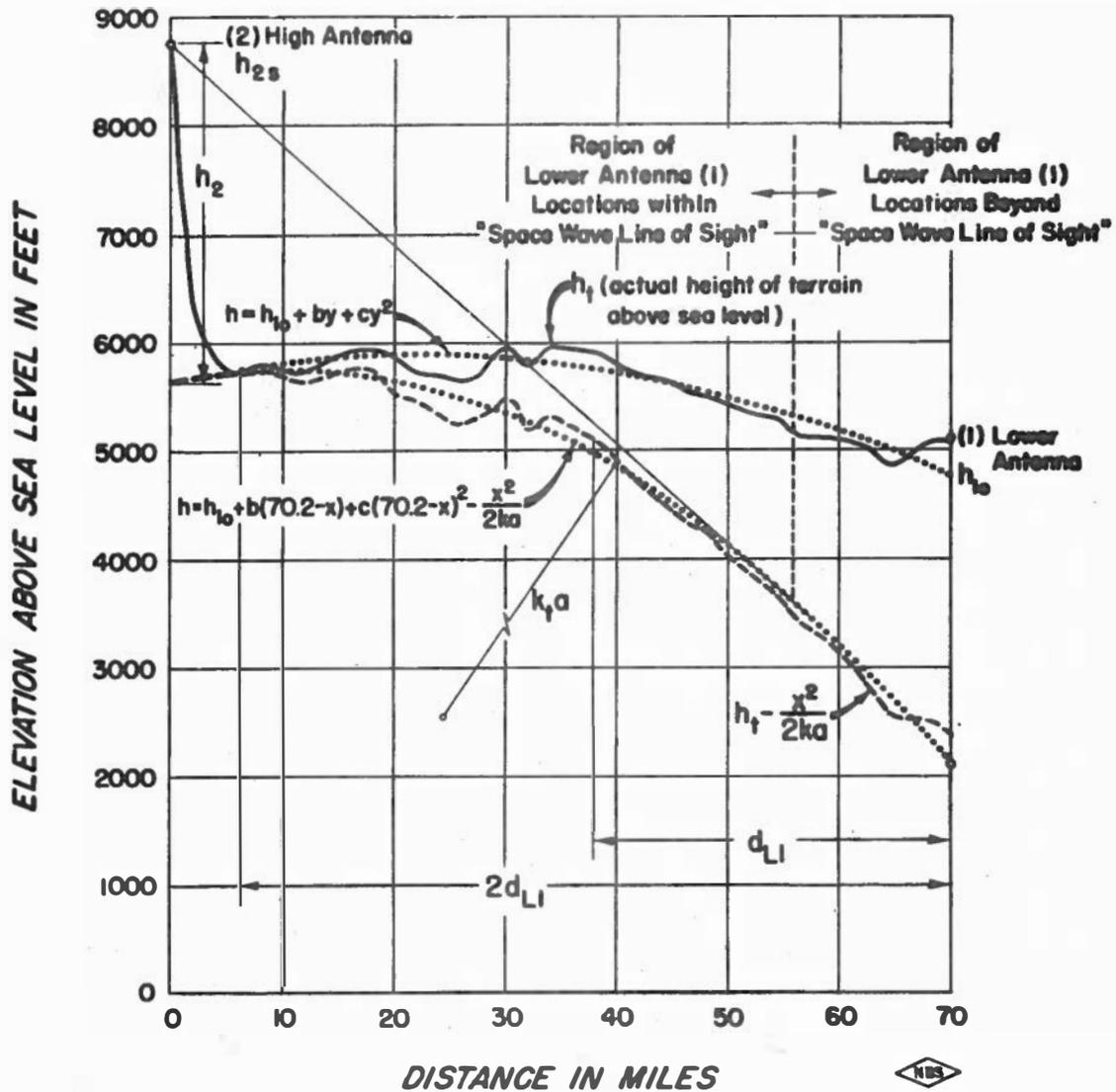


Figure 38

GEOMETRY FOR SPACE WAVE CALCULATIONS WITH A
CONCAVE OR A CONVEX SPHERICAL SURFACE OF
EFFECTIVE RADIUS $k_1 a$

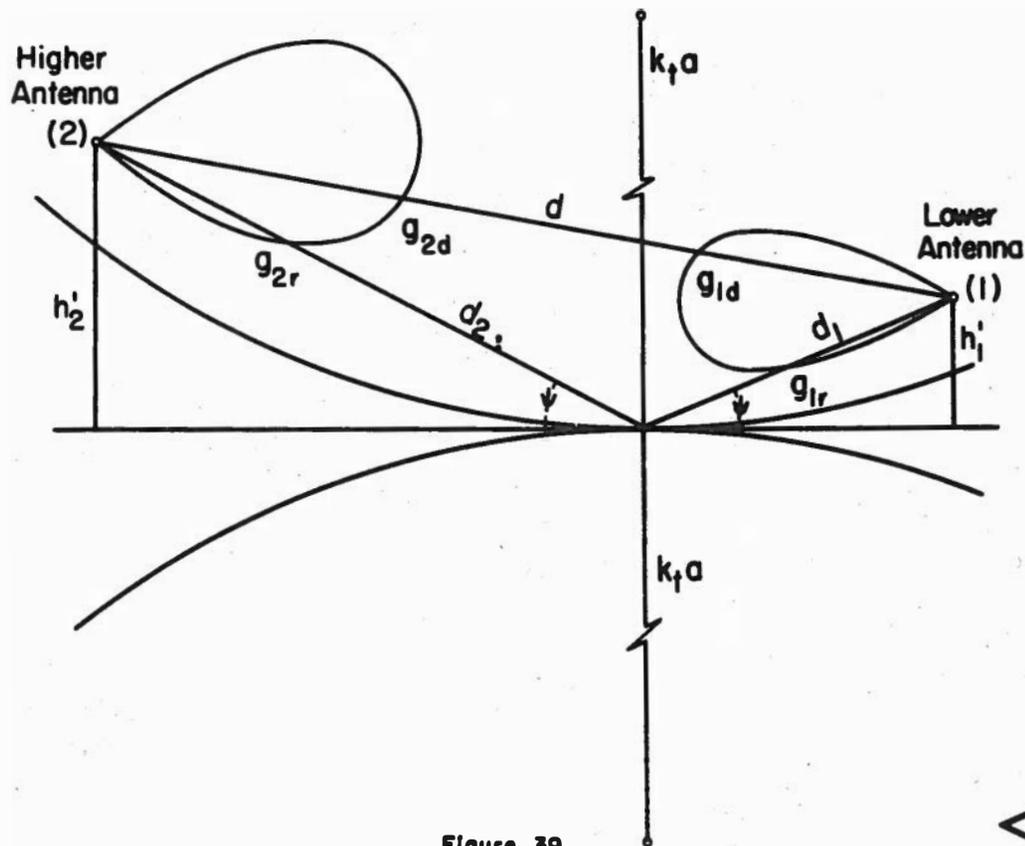


Figure 39



EFFECTIVE EARTH'S RADIUS, ka , ALLOWANCE FOR AIR REFRACTION

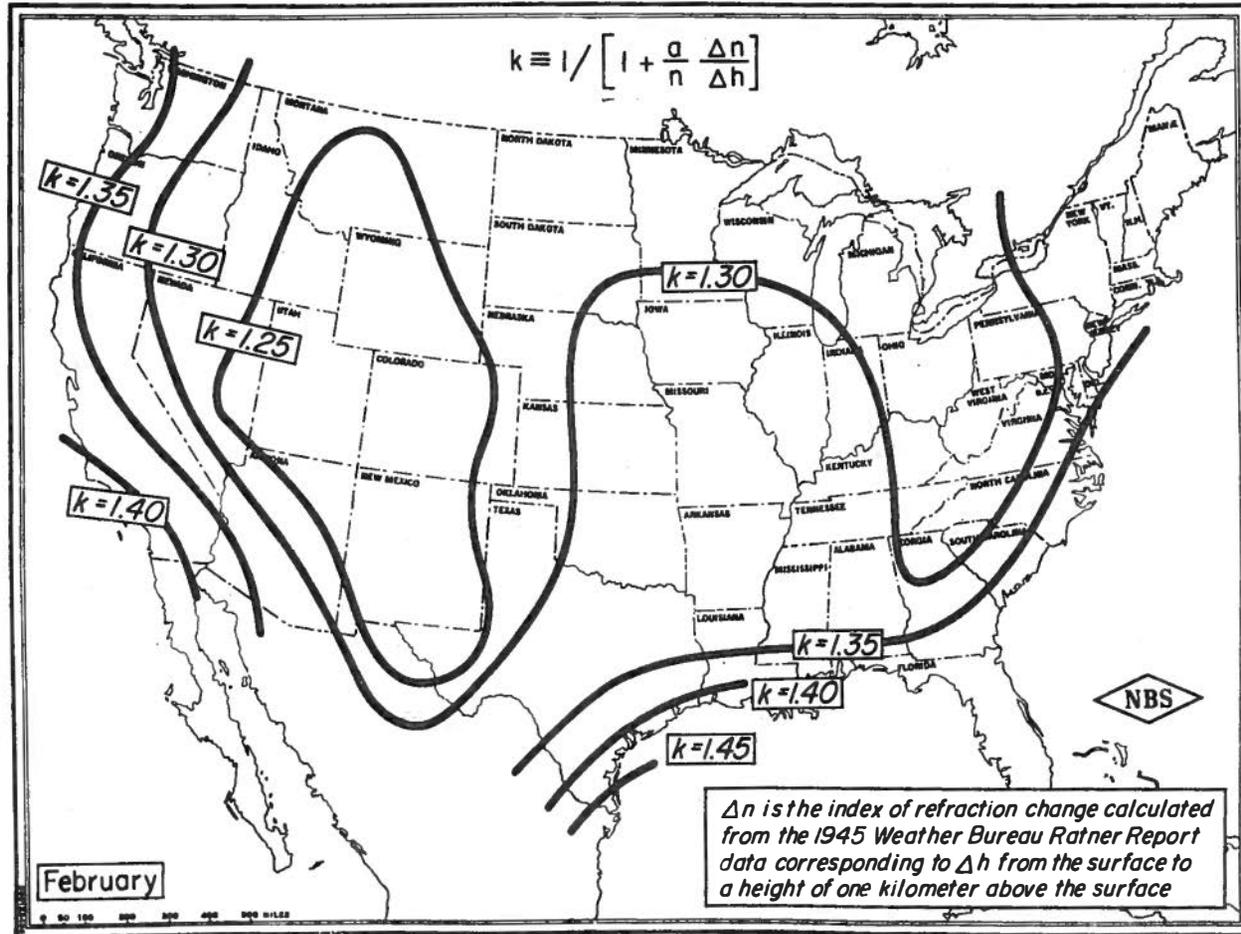


Figure 40

EFFECTIVE EARTH'S RADIUS, k_a , ALLOWANCE FOR AIR REFRACTION

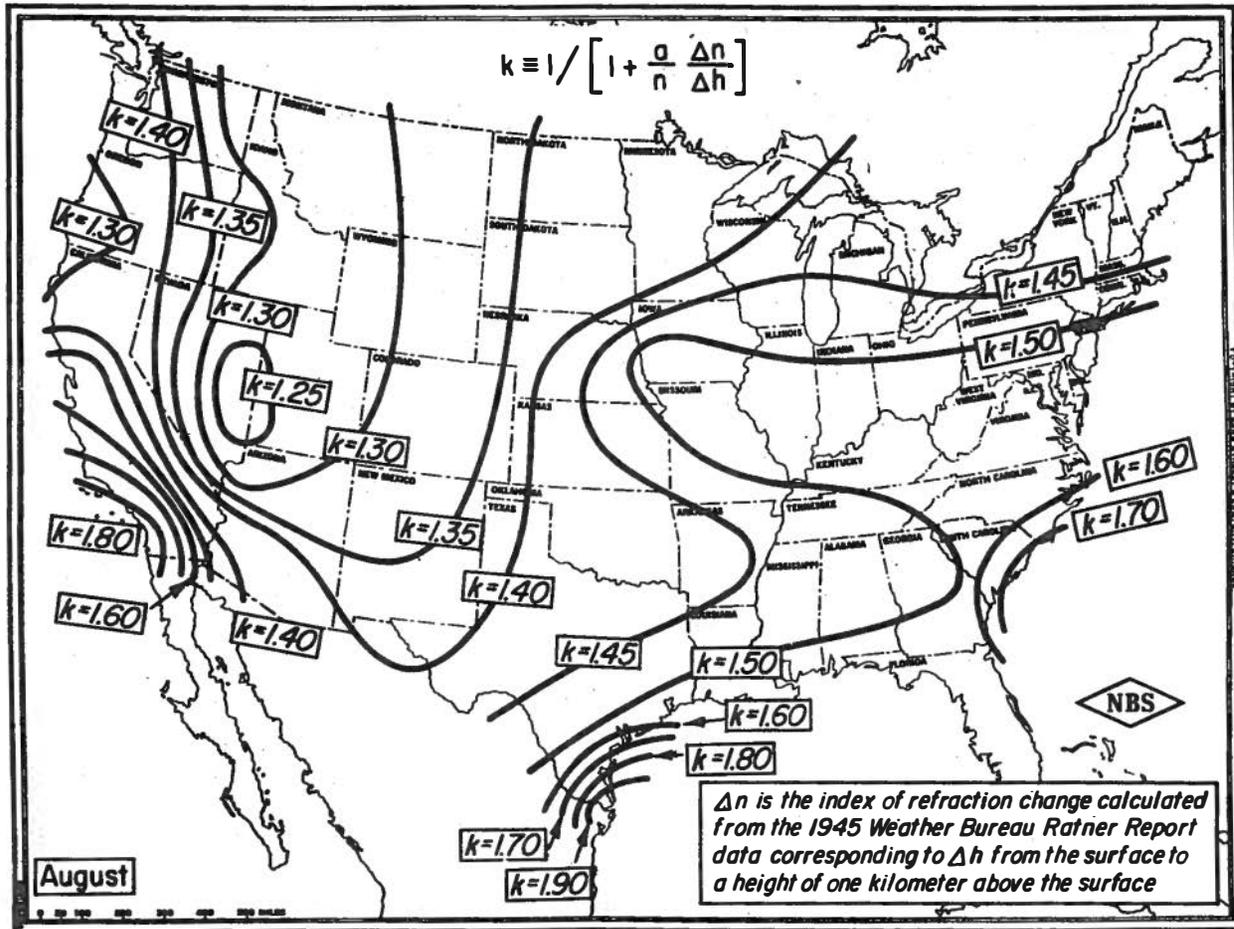


Figure 41

GEOMETRY FOR SPACE WAVE CALCULATIONS FOR RECEIVING POINTS WITHIN LINE OF SIGHT

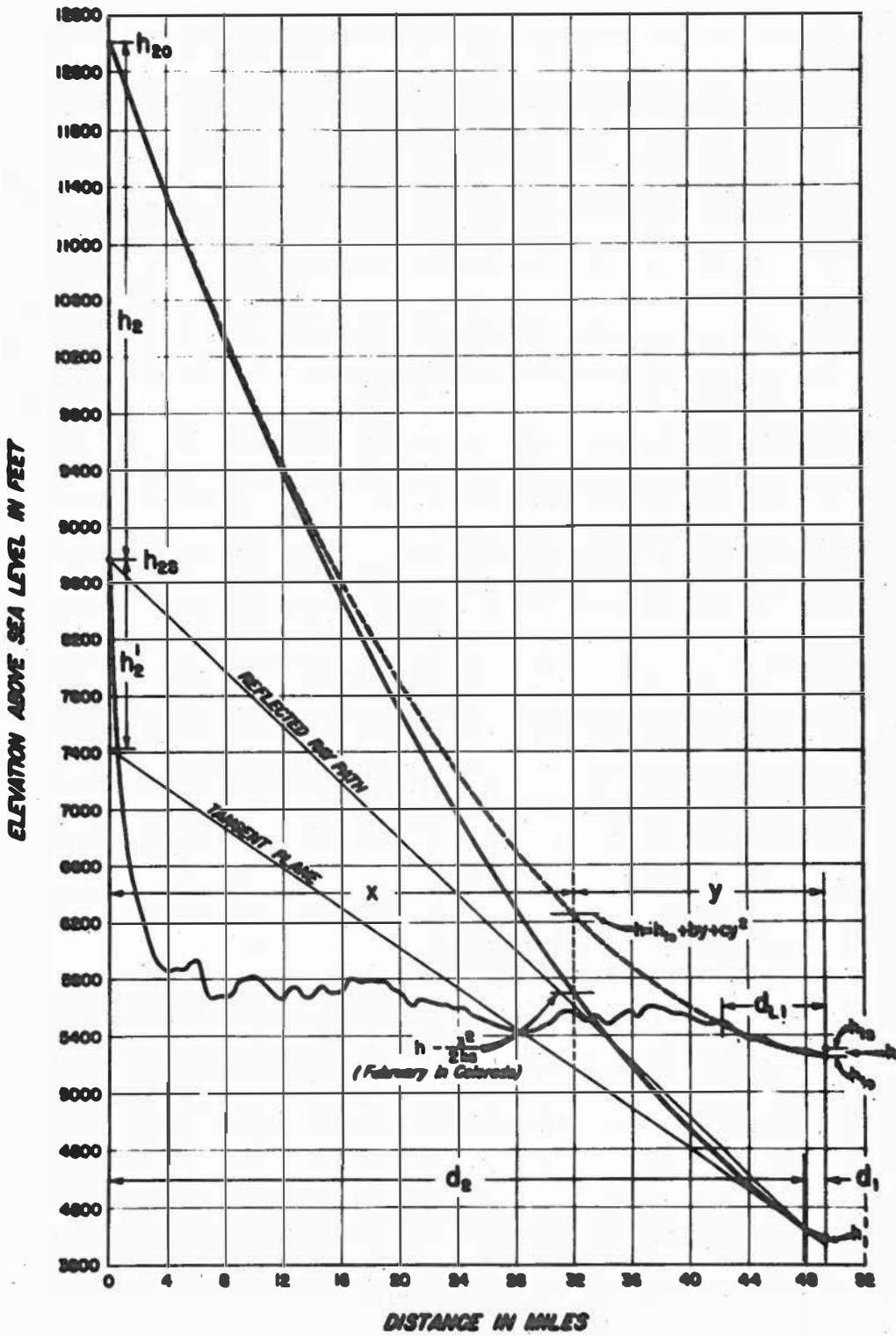


Figure 42



TERRAIN ANALYSIS FOR RECEIVING TERMINAL AT KENDRICK, COLORADO

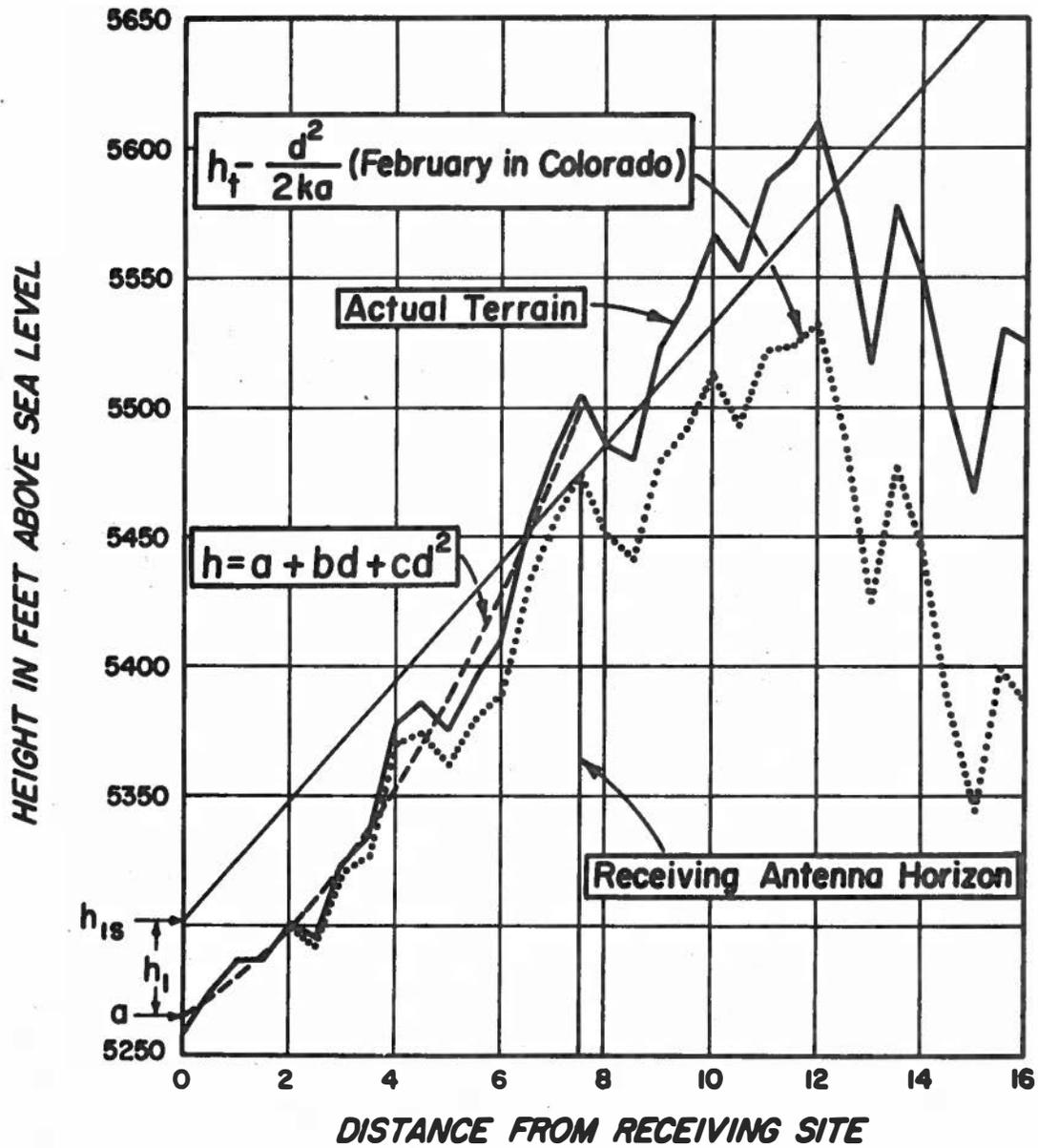


Figure 43



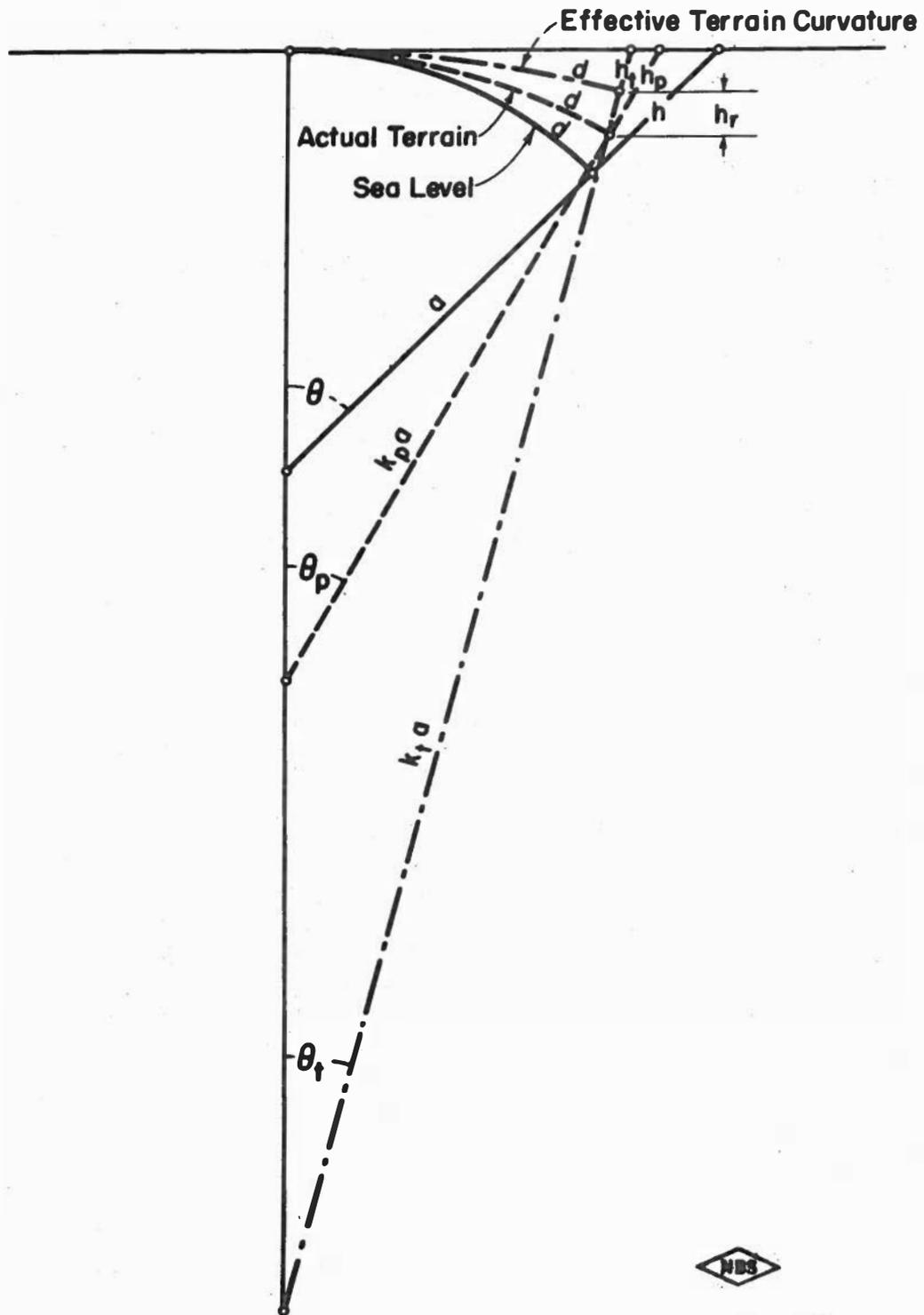


Figure 44

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services and various consultation and information services. A major portion of the Bureau's work is performed for other Government Agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the front cover.

Reports and Publications

The results of the Bureau's work take the form of either actual equipment and devices or published papers and reports. Reports are issued to the sponsoring agency of a particular project or program. Published papers appear either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three monthly periodicals, available from the Government Printing Office: The Journal of Research, which presents complete papers reporting technical investigations; the Technical News Bulletin, which presents summary and preliminary reports on work in progress; and Basic Radio Propagation Predictions, which provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: The Applied Mathematics Series, Circulars, Handbooks, Building Materials and Structures Reports, and Miscellaneous Publications.

Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards (\$1.00). Information on calibration services and fees can be found in NBS Circular 483, Testing by the National Bureau of Standards (25 cents). Both are available from the Government Printing Office. Inquiries regarding the Bureau's reports and publications should be addressed to the Office of Scientific Publications, National Bureau of Standards, Washington 25, D. C.