Report of U.S. Commission 2, URSI TROPOSPHERIC RADIO PROPAGATION

The USA National Committee of Commission 2 Tropospheric Radio Propagation, has been quite active since the XIIth General Assembly held in Boulder, Colo., 1957. This report contains a brief summary of the work of this Commission arranged in accordance with the topics to be discussed at the XIIIth General Assembly, London, 1960. The bibliography at the end of this report includes principally the papers published since the XIIth General Assembly. References to work that is not generally available in the published literature have not been included.

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1. Physical Characteristics of the Troposphere

1.1. Synoptic Scale

Studies on the synoptic scale [Bean, 1959 a, b] have shown that the radio refractive index, when referenced to sea level, is a sensitive indicator of departures from average of atmospheric structure due to tropospheric storms. Indeed, since this reduced-to-sea-level index combines temperature, pressure, and humidity into one term, it appears to have much to recommend it to the meteorologist as an aid in synoptic forecasting. Encouraging correlation has been found between standard weather map information and the variations with time of 1,000 and 10,000 Mc/s beyond the horizon radio fields [Moler, 1958a].

This same reduced-to-sea-level index has facilitated the preparation of world-wide contour maps of the refractive index near the earth's surface by effectively removing altitude dependence [Bean, 1959c]. These charts showing the annual cycle of the mean refractive index may be used to indicate not only climatic comparisons between various regions but also the stability or range of weather in different geographic areas. Studies of atmospheric refraction of radio waves [Anderson, 1958; Bauer, 1958a; Bean, 1959d] have shown that an exponential decrease of refractive index with height is more representative of the true structure and yields more reliable estimates of refraction effects than the linear decrease assumed by the effective earth's radius theory. The rate of exponential decrease with height may be specified by surface conditions alone [Bean, 1959d]. Consideration of these results led the CCIR Plenary Assembly in Los Angeles in April 1959 to recommend the international adoption of a basic reference atmosphere of exponential form.

A bibliography on the physical properties of the atmosphere at radiofrequencies has been collected and published [Nupen, 1957].

Further studies of the refractive index structure of the atmosphere will be facilitated by two newly established national data centers. The Electrical Engineering Research Laboratory of the University of Texas has accumulated approximately 2,700 airborne refractometer profiles from the North American, Mediterranean, and Hawaiian areas. The Central Radio Propagation Laboratory of the National Bureau of Standards has available approximately 50,000 individual radiosonde ascents taken by military and civilian observations in 40 different locations ranging from the arctic to the tropics.

A large percentage of the earth's atmosphere, and almost all of its water vapor, is contained in the troposphere. The atmospheric gases are more or less horizontally stratified over extended areas, and the gross effect is a gradual decrease in the dielectric constant with altitude. If this gradient of the average dielectric constant is independent of distance and time then the radio propagation problem reduces to a simply stated boundary value problem which might be called mode theory with many tiers of sophistication. These range all the way from simple ray optics approximations to intricate superposition of a large number of modes [Carroll, 1955]. To describe nonoptical fields, the first suggestion embraced the idea of replacing the problem of diffraction around the earth immersed in a nonhomogeneous atmosphere by diffraction around a sphere of different radius surrounded by a homogeneous medium. In this way, the gradual downward refraction of the radio waves would be accounted for by a larger earth's radius. This idea has been tested and it is found that the factor multiplying the earth's radius is not a simple function of the radiofrequency and the index of refraction profile.

Schelkunoff has proposed an approximate analysis of guided propagation which has been quite useful in determining the cutoff frequency for a given index of refraction profile. This method only states that frequencies above a certain value will or will not be strongly guided, the attenuation rate is not determined. Some success has been obtained in the application of this analysis to microwave propagation in the oceanic duct.

Airborne refractometer investigation [Ament, 1959a] found that the tradewind inversion between the east coast of Florida and Nassau (about 500 km), was consistently at an elevation of 1.5 km with a 50-N unit decrease across the inversion. The intensity of refractive index fluctuations within the layer were found to vary considerably with horizontal distance. Further work on refractive index structure of layers has been carried out by analysis of several thousand refractometer soundings over southwest Ohio and the west coast of Washington state [Moyer, 1958]. Both regions showed a preference for layer occurrence at a height of 1.75 km with the average vertical gradient just necessary for ducting (160 N units/km). Although the average layer thickness was of the order of 150 ms in both cases, the Washington coast layers were more evenly distributed between thicknesses of 60 and 210 m. Refractometer investigations have resulted in additional knowledge of humidity structure within elevated layers and also have shown that such layers can satisfy Rayleigh's criterion for smoothness for wavelengths perhaps as small as 1 m [Bauer, 1958b]. Further investigation utilizing airborne refractometers has revealed that the turbulent structure in converging air at 1.2 km is an order of magnitude greater than that found in diverging air within a high-pressure region [Wagner, 1957]. Similar investigations have shown that the "simple" trade wind cumulus cloud is in fact of the most complicated structure from the viewpoint of the refractive index [Cunningham, 1958]. Details of the temperature, humidity and refractive index structure of the trade wind region have been studied with radiosondes [Gutnich, 1958], catalogued in climatological atlases [U.S. Navy, 1955, 1956, 1957, 1958], and examined with airborne refractometers by the Naval Research Laboratories.

1.2. Refractive Irregularities

Progress in describing the radio refractive index structure of the atmosphere has been made on the micrometeorological scale by the use of airborne refractometers in the study of fundamental theories of turbulence. Two authors have attempted to calculate, using turbulent mixing theories, the spectrum of refractive index variations to be expected in a turbulent region possessing a mean gradient of refractive index, such as the troposphere or ionosphere. Wheelon [1957a, b, 1958a] has attempted to describe analytically the results expected from the gradient-mixing mechanism described earlier by Villars and Weisskopf. Bolgiano [1957, 1958a, b], extending the concept of isotropic-mixing theory to account for the presence of a gradient, does not modify the isotropic-mixing results in a range of interest, in contradiction with the conclusion reached by Wheelon [1958b].

Techniques similar to those employed by Heisenberg for velocity fields have been applied to an investigation of temperature fluctuations in a turbulent region [Ogura, 1958]. Also investigated theoretically was the generalization of mixing by isotropic turbulence to include the effect of a simple chemical reaction on the concentration field [Corrsin, 1958].

A marked disagreement has been expressed [Kraichnan, 1957, 1959; Munch, 1958] as to the seriousness of the error introduced by the assumption that the fourth-order moments of the two-time velocity amplitude distribution are related to second-order moments as in a normal distribution. This quasi-normal approximation has been made in order to calculate the space-time correlation in stationary isotropic turbulence [Munch, 1958].

One theory [Kraichnan, 1958a, b] of unbounded turbulence, driven by Gaussian-distributed homogeneous forces, was developed which gives a wavenumber spectrum which is a function of the rms velocity, in contradiction to the Kolmogorov similarity hypothesis.

Two articles extend Chandrasekhar's results on the spectrum of turbulence, one [Blanch, 1959] giving improved numerical results and comments on the choice of equations for numerical evaluation and the other [Wentzel, 1958] working out the spectra for specific examples.

A general power-spectrum equation, basically empirical, for stationary random gusts has been obtained [Saunders, 1958].

Booker continued a discussion of a previously presented concept of a mechanism connected with ionospheric turbulence and meteor trails [Booker, 1958].

Results based on the energy transfer mechanism suggested by Kovasznay have been used to calculate solutions for the energy spectrum and the transfer function in the initial period of decay [Reid, 1959].

Other theoretical investigations have been concerned with turbulent-flow equations [Squire, 1959] and with the relation between time symmetry and reflection symmetry [Meecham, 1958].

The concept of a "locally stationary random process" has been rigorously defined and discussed [Silverman, 1957a; Ogura, 1957; Dryden, 1957].

A possible influence of the mean stability and shear on the spectrum of turbulence, and indirectly on the spectrum of refractive index fluctuations, has been discussed by Bolgiano [1960], who has suggested that this effect may account for the variable wavelength dependence of scatter propagation [Bolgiano, 1959]. However, Norton [1960] reanalyzed the data employed by Bolgiano, and concluded that they could not be interpreted as indicating a variable frequency dependence; he found that the fixed-frequency dependence 30 $\log_{10} f_{\mathrm{Mc/s}}$ of the basic transmission loss derived from the $\rho K_1(\rho)$ correlation model for the refractive index was in agreement with the data. Norton [1959a] has published an analysis of the agreement of the $\rho K_1(\rho)$ model with three independent kinds of experimental evidence: (a) Frequency spectra of refractivity; (b) frequency spectra of the phase variations on a line-of-sight path; and (c) the frequency dependence of tropospheric forward scattered power. He concludes that all of these data are in agreement, within experimental error, with this model. In a note at the end of the paper, he calls attention to the fact that the improved data recently published by Thompson and Janes [1959a] appear to indicate that it is not safe to assume that the variations in time of the refractive index at a fixed point may be described by the assumption that a frozen structure, described by a wavenumber spectrum, is moved past this point with the mean wind.

Observations of smoke puffs [Gifford, 1957] and stack gases [Hilst, 1958] have been compared with diffusion theories. Other investigations compare spectra obtained from concurrent airplane and tower measurements [Lappe, 1959] and compare simultaneous observations of space correlations and time correlations [Panofsky, 1958].

Velocity spectra have been deduced from the average rate at which a radar signal crosses a given voltage level [Fleisher, 1959]; the effects of wind speed, lapse rate, and altitude on the velocity spectrum at low altitudes has been studied [Henry, 1959]; the power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 c/hr have been measured [Van der Hoven, 1957]; and data obtained by flight test techniques have been analyzed to determine how well the velocity variations satisfy the conditions of a stationary Gaussian process and of isotropic turbulence [Press, 1957].

Turbulence measurements have been made for general clear-air conditions [Anderson, 1957; Clem, 1957], near jet streams [Endlich, 1957], near [Ackerman, 1958] and in [Ackerman, 1959] clouds, and associated with a cold front (radar observations) [Ligda, 1958a].

Eddy sizes near the ground have been determined by measurements of temperature [Longley, 1959].

1.3. Absorption in the Troposphere

During recent years generators and components have been improved to the extent that absorption measurements of the actual atmosphere could be made in the millimeter wavelength region. Such measurements have been made by Crawford and Hogg [1956] in the 5- to 6-mm region and at 4.3 and 3.55 mm, and by E. E. R. L. of the University of Texas [Tolbert, 1959a] in the range 1.2 to 1.7 cm, at 8.6, 4.3, 3.55, 2.15 mm, and at a number of wavelengths in the range from 2.5 to 3 mm. The comparisons of the measured losses with those calculated from the Van Vleck-Weisskopf equation are shown in figures 1 and 2. It is seen that the agreement between theory and experiment is good in the case of atmospheric oxygen using the value of 0.02 cm^{-1} for the 5-mm lines. In the case of atmospheric water vapor, however, the agreement is poor, no one line width fitting the entire data. Moreover, the line width of 0.1 cm^{-1} or 0.27 cm^{-1} does not give a completely satisfactory fit for the region around 1.35 cm or the higher frequency region, respectively.

The recent advances on the determination of the line width parameters may be summarized as follows. Benedict and Kaplan [1959], using the quantum theory of Anderson, find that the line widths in H_2O–N_2 collisions vary from 0.111 to 0.032 cm^{-1} atm^{-1}. Such values indicate that an often quoted average value of 0.1 cm^{-1} atm^{-1} may actually be on the high side. Laboratory measurements of the nonresonant absorption in pure oxygen by Maryott and Birnbaum [1955] give a value of 0.017 cm^{-1} atm^{-1}. The line width parameter they found necessary to fit the resonant absorption, namely 0.05 cm^{-1} atm^{-1}, is in agreement with the work of Artman [1954].

The discrepancy between theory and experiment in the case of water vapor absorption has long been the cause for examining the limits of applicability of the Van Vleck-Weisskopf theory. Gora [1956] has recently reviewed the situation and finds that no important modification of their equation is needed until the 1-mm region is reached.

Recent measurements by Maryott, Wacker, and Birnbaum [1957] have revealed absorption by the nonpolar gas CO_2 due to collision-induced dipole moments. Although such absorption in atmospheric CO_2 is far too small to play a role, it suggests a direction in which one might look for an explanation of the absorption anomaly. In this connection, Birnbaum and Maryott have found that a large part of the absorption in the microwave wings of the infrared rotational lines of HCl and DCl can be accounted for by assuming the presence of pressure-induced absorption.

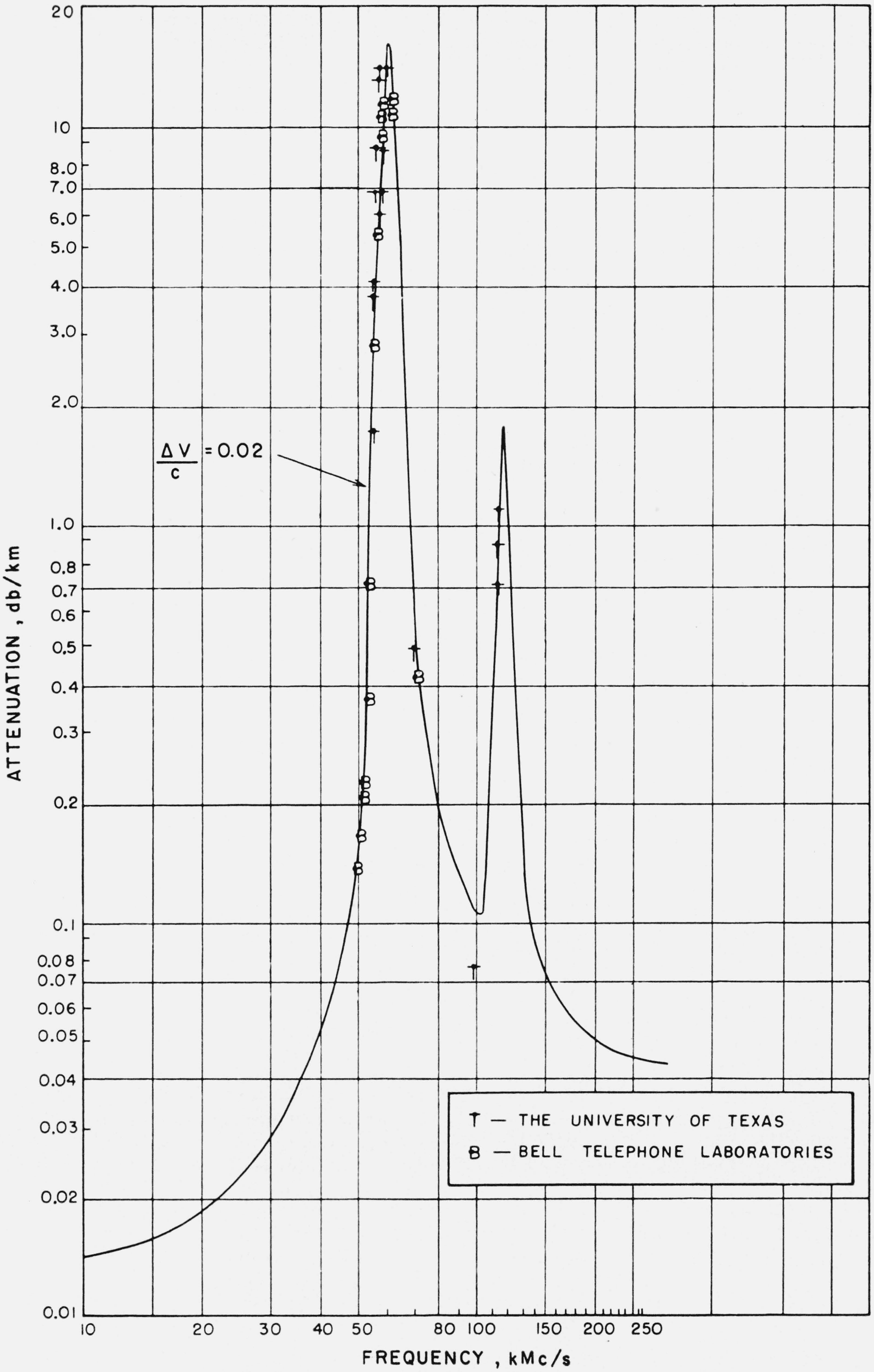

FIGURE 1. *Attenuation due at one atmosphere.*

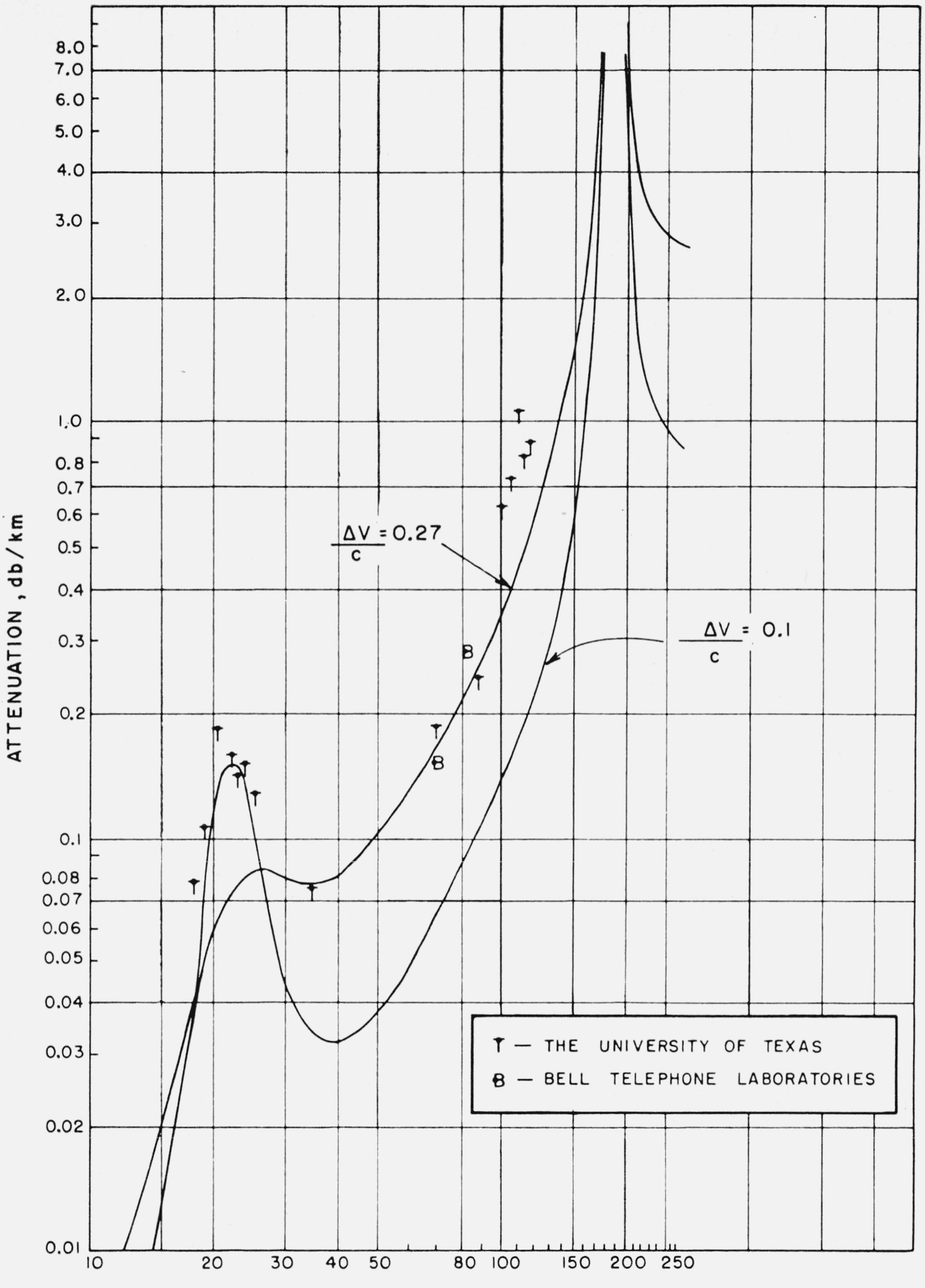

Figure 2. *Water vapor attenuation for 7.5 grams per centimeter.*

2. Tropospheric Propagation (Theories)

2.1. Ground Wave Propagation

Renewed interest in the VLF band has prompted several investigations concerning the propagation characteristics of groundwaves. In the range below 100 kc/s the groundwave may compete with and can often exceed the skywave. Furthermore, with the use of pulse type transmissions such as Cytac or Loran C, the groundwave and skywave may be observed separately [Frantz, 1957; Dean, 1957; Frank, 1957]. This is not possible, of course, in a CW system such as Decca. It is also essential to take proper account of the groundwave in the analysis of sferics which are radio signals originating from distant lightning strokes.

With the above motivation (if such is needed) several theoretical investigations of groundwave propagation have been carried out [Wait, 1958a]. Using the residue series representation as developed, graphs and tables of attenuation and phase for CW transmission have been prepared [Johler, 1956, 1959a; Wait, 1956a]. The frequency range is from 100 c/s to 500 kc/s and various ground constants and antenna heights where chosen. These curves are presented in terms of field strength and they are normalized for a dipole transmitter of fixed moment.

Theoretical groundwave investigations have included studies of methods to include variations of the refractive index of the troposphere. As mentioned under the section of this report dealing with the synoptic scale variations of the physical characteristics of the troposphere, (sec. I, 1), the usual method of accounting for the gradual downward bending of radio waves is to replace the actual earth's radius a by an effective earth's radius a_e. The ratio a_e/a is usually taken to be about 4/3. It has been shown [Wait, 1958*b*] that such a procedure is a mathematically adequate approximation for propagation in a standard type atmosphere if the antenna heights are not too high (i.e., less than 1 km) and if the frequency is not too low (i.e., greater than about 50 kc/s). When either of these conditions is violated, it is necessary to consider the influence of nonlinearity in the lapse rate of the refractive index with height. Theoretical studies have been carried out which indicate that the diffraction theory for a 4/3 rds earth may be simply modified for an atmosphere whose refractive index varies with height in a smooth monotonic fashion [Wait, 1958b]. The essential conclusion is that the structure of the diffraction field near and beyond line-of-sight is similar to that for a homogeneous atmosphere. Thus the available calculated results based on the 4/3 rds. earth may be simply adapted to the tapered model by simply shifting the horizon point which is calculable using geometrical or ray optics. Such a procedure had been used earlier by K. A. Norton [1958] which, at the time, was justified on physical grounds.

All the "eigenvalue" or "proper value" solutions suffer from some difficulties. The problem is centered around the determination of the complex propagation constants associated with the dominant modes. These numbers are extremely sensitive to the detailed structure of the index of refraction profile. A given experimental refractive index profile can be represented by numerous smooth curves, each yielding a different mode sum for the radio field.

In addition, the sensitivity depends upon the wave function accepted as a solution; for example, if the well-known WKB approximation is considered an appropriate wave solution, continuous index of refraction profiles with continuous first order derivatives will yield no "proper values" since there is no way to couple the field of the up-going wave with the field of the down-going wave.

The influence of a land sea boundary has been given further study. A solution has been presented for a smooth earth for a mixed path with both two and three sections. Numerical results for amplitude and phase over a frequency range of 20 to 200 kc/s are also available [Wait, 1957a].

The propagation of electromagnetic pulses over a smooth homogeneous earth has been given considerable attention from a theoretical point of view [Wait, 1956b, 1957b, c, 1959a; Johler, 1957, 1958, 1959b; Levy, 1958]. For low frequencies the dispersion of the pulse is due mainly to the influence of earth curvature. The finite conductivity of the ground plays a relatively minor role. Some thought has also been given to the influence of a coast line on the shape of a groundwave pulse [Wait, 1957d].

It was pointed out that the presentation of groundwave propagation data in terms of transmission loss requires that the input impedances of the antennas be considered [Wait, 1959b; Norton, 1958]. Various methods of calculating transmission loss of the groundwave are reviewed in a comprehensive paper [Norton, 1959b].

The penetration of the groundwave into the earth or the sea has been considered in several recent papers [Wait, 1959c, d; Kraichman, 1960; Keilson, 1960]. Both buried transmitting and receiving antennas have been considered.

The influence of ground stratification has been given some attention [Wait, 1958c]. It is indicated that the attenuation of the groundwave may be quite low if the underlying stratum is highly conducting and located at an appropriate depth. The measurements are in accord with theory [Stanley, 1960].

2.2. Backscattering From Rough Surfaces

Katzin [1957] has continued his theoretical development of backscattering from a sea surface. He has extended to high-depression angles the statistical treatment previously made for low angles. He finds that σ_0 varies as λ^{-n} for frequencies in the region where the facets are small compared to a wavelength. As the frequency increases a region is reached where the facets are large compared with λ; above this region, σ_0 is constant with further increase in frequency. He also finds σ_0 is inversely proportional to wind speed and that the depression angle dependence is $\exp(-\cot^2\theta/2\sigma^2)$.

Spetner and Katz [1960] have approached radar backscattering from a statistical point of view. They calculate the normalized radar cross section, σ_0, for two different terrain models. The first model is a distribution of independent scatterers. For this model σ_0 is independent of depression angle, θ, but has a local wavelength dependence as λ^n, where n can be -6, -4, or -2. The second model is a surface of specular points where the slope distribution is Gaussian. Here, for small λ, σ_0 varies as $k\lambda^{-2}$ $\exp(-\cot^2\theta/2\sigma_s^2)$. For large λ the relationship depends on the surface slope spectrum. For a flat spectrum, whose cutoff wave length is λ_2, σ_0 varies as $k_1\lambda^{-6}\exp(-\lambda\cot^2\theta/2\lambda_2\sigma_s^2)+k_2\lambda^{-6}$ and for a spectrum with a single peak the σ_0 relationship is $k\lambda^{-6}$.

Moore [1957] has obtained the same angular dependence, using a model based on random distribution of heights of facets:

$$\sigma_0=\frac{(90^\circ-\theta)a^2\sec\theta}{4\pi\sigma^2}e\;-a^2/4\sigma^2\cot^2\theta.$$

Here a is the horizontal correlation distance of height and σ is the standard deviation of height. The specular return is reduced by $e^{-2}(2\pi\sigma/\lambda)^2$ from the smooth surface value.

2.3. Theory of Propagation Through a Stratified Atmosphere

The earth-flattening approximation has been used widely in the theory of a stratified atmosphere to obtain approximate solutions for various types of refractive index distributions. In a refinement of the earth-flattening procedure, Koo and Katzin [1960] have shown that this procedure may be made exact, so that it may be applied for arbitrarily large heights and distances. Furthermore, it is found that existing solutions for the height-gain function obtained with the use of the previous earth-flattening approximation can be made to give the exact solutions for a slightly different refractive-index distribution. This method, which has been developed for spherical geometry, can be extended to other separable shapes.

In an extension of this work, Katzin has shown that mathematical approximations introduced to facilitate the solution of propagation problems can be interpreted as a change in the physical problem which is being solved. Thus, in the normal mode solution for propagation through a homogeneous atmosphere around a spherical earth, the WKB (tangent) or Hankel approximations for the eigenvalues are found to be the exact eigenvalues for a slightly inhomogeneous atmosphere, the inhomogeneity being different for the two approximations. In general, the approximations introduced represent a change in the refractive index distribution, in the geometry, or in both.

2.4. Line-of-Sight Scintillation

The electromagnetic response of a wave to a statistically irregular refractive index structure,

$$n(r,t)=n_0+\Delta n(r,t),$$

is well approximated by the basic wave equation:

$$\{\nabla^2+k^2[n_0+\mathbf{\Delta n}(r,t)]^2\}\vec{E}=0, \qquad (1)$$

where $k=2\pi/\lambda$ is the free space wavenumber and $\vec{E}(r,t)$ the developing electric field. It still does not seem to be possible to solve eq (1) exactly, since $\mathbf{\Delta n}(r,t)$ is an a priori unknown stochastic function of position and time. Hence, we can conveniently group research according to the approximate methods which have been used to solve the basic wave equation.

The ray theory or geometrical optics approximation to the solution of eq (1) has proven valuable in studying phase fluctuations in the Fresnel scattering regime, but is generally not adequate to predict amplitude variations, time and space correlation of phase records; and the appropriate correction factors for finite data sample and aperture smoothing limitations have been derived [Wheelon, 1957c] for an arbitrary model (spectrum or correlation) of tropospheric irregularities which are statistically stationary and homogeneous. Explicit expressions for finite aperture smoothing corrections were reported [Levin, 1959]. Corresponding results for angle-of-arrival variations are also given [Wheelon, 1957c]. A summary of all explicit geometrical optics calculations is presented in table 2 of Wheelon, 1959.

The single scattering or Born approximation has been widely used to study both phase and amplitude scintillations. Early calculations were based on particular models of the irregularities. However, a new approach was presented [Wheelon, 1957c] and further developed [Wheelon, 1959] which permits one to isolate the electromagnetic propagation calculations from the spectrum or correlation function. A model choice can thus be delayed until all electromagnetic calculations have been both completed. The relay-link and radio-star problems have been treated with this new method, and a technique has been devised [Wheelon, 1959] to study the complicated effects of ground reflections, aperture smoothing, and time and space correlations within the framework of a single scattering theory. Almost all of the previous calculations dealt exclusively with continuous wave transmissions, whereas Bugnolo [1959a] discusses the effect of the time variability of refractive irregularities on signal bandwidth and information capacity. Two investigations [Balser, 1957; Stein, 1958] into scattering of a vector field clarified several questions about the validity of previous scalar treatments, and discussed the effect of certain small terms which were dropped in writing eq (1).

A novel approach to the problem of stochastic propagation based on earlier astrophysical work is given [Bellman, 1958]. The basic idea is to replace the linear second order differential eq (1) by a nonlinear first order (Ricatti) differential equation, whose solution is identified with the reflection or transmission coefficient directly. This technique has not yet produced explicit answers of the type previously derived with ray theory, and will bear further research.

Statistical properties of a constant vector plus a Rayleigh-distributed vector were investigated further. Such a combination is presumably a good representation of the vector voltage diagram of line-of-sight signals containing both the free space and scattered signal components. Previous papers [Wheelon, 1959] had discussed the distributions of phase and amplitude at a single time. The mean square phase and average phase of such a combination were computed explicitly [Johler, 1959c] as a function of the mean signal to rms amplitude ratio. Bremmer [1959] considers the distributions of amplitude and phase at two different times.

2.5. Scatter Propagation

a. Layers

There has been no comprehensive treatment of the theory of beyond-the-horizon propagation via stratified layers in the atmosphere during the past two years in the United States. However, several papers have been published which provide evidence supporting reflections from layers as an important mechanism in the propagation. Airborne refractometer and meteorological measurements offer direct evidence of layers with sufficiently sharp gradients over sufficiently small intervals of height to provide reflection [Bauer, 1956] while [Bauer, 1958b] offers an explanation for the occurrence of layers. Substantial propagation data [Crawford, 1959] have been interpreted in terms of the reflection theory [Friis, 1957]. Correlation between signal characteristics and gross layer characteristics has been observed [Bauer, 1956; Barsis, 1957]. Time delay measurements [Chisholm, 1957a] airborne long distance measurements, and rapid antenna scanning [Ames, 1959a] have produced results that are not inconsistent with layer reflection.

b. Blobs

Activity in the field of tropospheric scatter propagation has been less intense in the last two years than previously. This diminished endeavor probably reflects the rather thorough exploitation of the turbulent scattering model which has been achieved in previous years. For example, it appears that almost nothing has been written about coherent partial reflection in the past several years, but several papers suggesting scattering by layers [Friis, 1957] or multiple scattering by blobs [Kay, 1958; Ament, 1960] have appeared. It is worth mentioning that the formalism introduced by Staras [1955] for taking into account anisotropy in the blob-structure bridges the gap between the spherical blobs introduced by Booker and Gordon [1950, 1957] and the layers introduced by Friis, et al. [1957].

A summary on the theoretical progress in tropospheric scatter propagation has appeared recently [Staras, 1959a]. That summary restricted its consideration to single scattering. Diffraction and ducting effects are neglected in single scattering for lack of a tractable solution. The generally stratified average atmosphere [Misme, 1958] enters only through ray bending, allowing more or less favorably situated blobs to enter in the single-scattering phenomenon. The dominant parameter in a single-scattering theory is the autocorrelation function of the random irregularities which in turn is related to the spectrum of these very same irregularities. Thus, the characteristics of over-the-horizon propagation make contact with the various models of atmospheric turbulence [Wheelon, 1957a; Bolgiano, 1958a; Paul, 1958; Silverman, 1957b]. This has already been discussed previously [Staras, 1959a]. It should be emphasized though that the fundamental role of the spectrum of refractive-index irregularities as opposed to that of the correlation function has been clearly established. This is most important since attempts at empirical determination are at best estimates over a limited range of values; and limited knowledge of one member of the Fourier transform pair cannot yield positive identification of the other. In addition, evidence both from radio investigations and meteorology indicate that atmospheric spectra vary not only in intensity, but also in shape. This emphasizes the danger of assuming a unique form for the refractive-index spectrum as has been discussed by Bolgiano [1959] who suggested that the variable form for the refractive-index spectrum may account for the variable wavelength dependence of scatter propagation. However, in a recent analysis Norton [1960] states that the wave number refractivity spectrum pertinent to the forward scatter of radio waves *cannot* be directly measured when the medium is anisotropic. He proposes a scheme for a direct measurement of the refractivity characteristics of the atmosphere leading to an anisotropic correlation function which could then be transformed into the appropriate wave number spectrum.

An aspect of single scatter theory which is receiving increased attention lately is angle diversity [Bolgiano, 1958c; Vogelman, 1959]. This is intimately related to the concept of antenna coupling loss developed earlier [Booker, 1955; Staras, 1957, 1959b; Hartman, 1959]. Since antenna coupling loss is believed to arise from a failure to fully illuminate the effective scatter volume when the antenna becomes very large, some investigators have suggested that a multiplicity of feeds in a very large parabolic antenna could be used to illuminate the entire scattering volume and thereby cut down on the coupling loss. While this is undoubtedly true, it is indicated [Staras, 1960] that there may be easier and more standard ways of achieving the same result as would be accomplished by angle diversity.

In summary, it appears that the major development in transhorizon tropospheric propagation during the past several years in the growing body of evidence indicating that no single mechanism (scattering, reflection from layers, ducting, etc.) can account for all the experimental results. Typical of this are Crawford, Hogg, and Kummer's experiments [1959]. They appear to support a scatter model 60 to 70 percent of the time and a layer reflection model much of the remainder. From Staras' [1955] point of view, this experimental result would suggest that the anisotropy in scatter propagation is highly variable. Recent work on multiple scattering [Kay, 1958; Ament, 1960] and scattering by layers [Friis, 1957] should also prove to be useful for explaining some of these other mechanisms.

However, for that part of the time when scattering is expected, single-scattering theory has been used with essentially no adjustable parameters to provide a satisfactory explanation of forward scatter data [Nortom, 1959b; Rice, 1959].

3. Experimental Results From Investigations of Tropospheric Propagation

3.1. Attenuation With Distance

Recent experimental data on beyond horizon tropospheric transmission have provided very useful information at distances up to 1,200 km. Most of the new results are in the frequency range below 500 Mc/s. These data together with earlier information clearly establish that the decrease in signal level at the greater distances follows an exponential law at a rate of about 0.075 db/km near the surface. Airborne measurements have corroborated that the path loss depends upon the "angular" distance between the two terminals, not upon the surface distance alone.

Figure 3 shows observed median values of beyond horizon basic transmission loss plotted versus distance and coded by frequency groups for a large, heterogeneous sample of U.S. data, obtained in most cases with broad beam antennas. No normalization for the effects of frequency, antenna height, angular distance, path asymmetry, terrain, time of day or season, or climatic parameters is included. Most of the spread of the data, in addition to that caused by changes in frequency, appears to be due to the diversity of antenna heights and terrain represented by the actual propagation paths. Differences in atmospheric conditions appear to be the next most important consideration.

Some experimental data, particularly for transmission over water, show a 5- to 10-db hump in the curve in the neighborhood of 300 to 500 km. This is not clearly understood, but it may be significant that the volume of the atmosphere visible from both transmitting and receiving antennas for this case is at elevations of 2 to 4 km where most of the visible clouds occur.

Two sets of curves are compared with the data. One is based on the assumption that basic transmission loss varies as the second power of the frequency; these curves were approved by the CCIR in April 1959, for frequencies up to 600 Mc/s and for antenna heights of 10 and 300 m. The other set of curves is calculated for a smooth earth of effective radius 9,000 km, for antenna heights each equal to 10 m, and for various frequencies, assuming an exponential decay of refractive index with height such that the refractive index is $1/e$ times the surface value at a height of 6.9 km. Frequency dependences are influenced by the nature of the terrain and atmosphere and by whether antennas are high or low; these factors determine the dominance of various propagation mechanisms. The large influence of antenna height is illustrated in figure 4 which shows theoretical smooth earth curves for a frequency of 500 Mc/s with one antenna height fixed at 10 m and the other varying from 10 to 100,000 m.

In temperate latitudes the seasonal variation of received signals shows a minimum during the winter, and the diurnal trend has its minimum in the afternoon. These minima are on the order of 10 db below the annual median value, except that diurnal trends are less pronounced at great distances. Since the signal level depends to some extent on atmospheric refraction, the median signal level in low latitudes is usually higher than in the high latitudes.

Data from the following sources have been considered in the preparation of this report and the accompanying chart:

1. Federal Communications Commission Technical Information Division Reports 2.4.6, May 1949; 2.4.10, October 1950; 2.4.13, December 1954; 2.4.16, October 1956; and private communications.
2. National Bureau of Standards Reports 1826, July 1952; 2494, May 1953; 2539, May 1953; 3536, March 1954; 3520, January 1955; 3568, February 1956; 5067, December 1956; 5072, May 1957; 5524, October 1957; 5582, June 1958; 6019, November 1958; and NBS Circ. 554, January 1955.
3. Proc. IRE, Vol. 43, No. 10, October 1955, pp. 1306–1316. Proc. IRE, Vol. 43, No. 10, October 1955, pp. 1369–1373. Proc. IRE, Vol. 43, No. 10, October 1955, pp. 1488–1526. Proc. IRE, Vol. 46, No. 7, July 1958, pp. 1401–1410.
4. IRE Summary of Technical Papers, 4th National Aero-Com Symposium, October, 1958.
5. Bell System Technical Journal, September 1959.
6. International Telephone and Telegraph Corporation, Federal Telecommunication Labs., Technical Memo 566, November 1955.
7. Air Force Cambridge Research Center AFCRC February, 1958, private communication. Air Force Cambridge Research Center AFCRC–TR–55–115, June 1955 (see also Ames, 1959a).
8. Massachusetts Institute of Technology, Lincoln Labs., private communication.

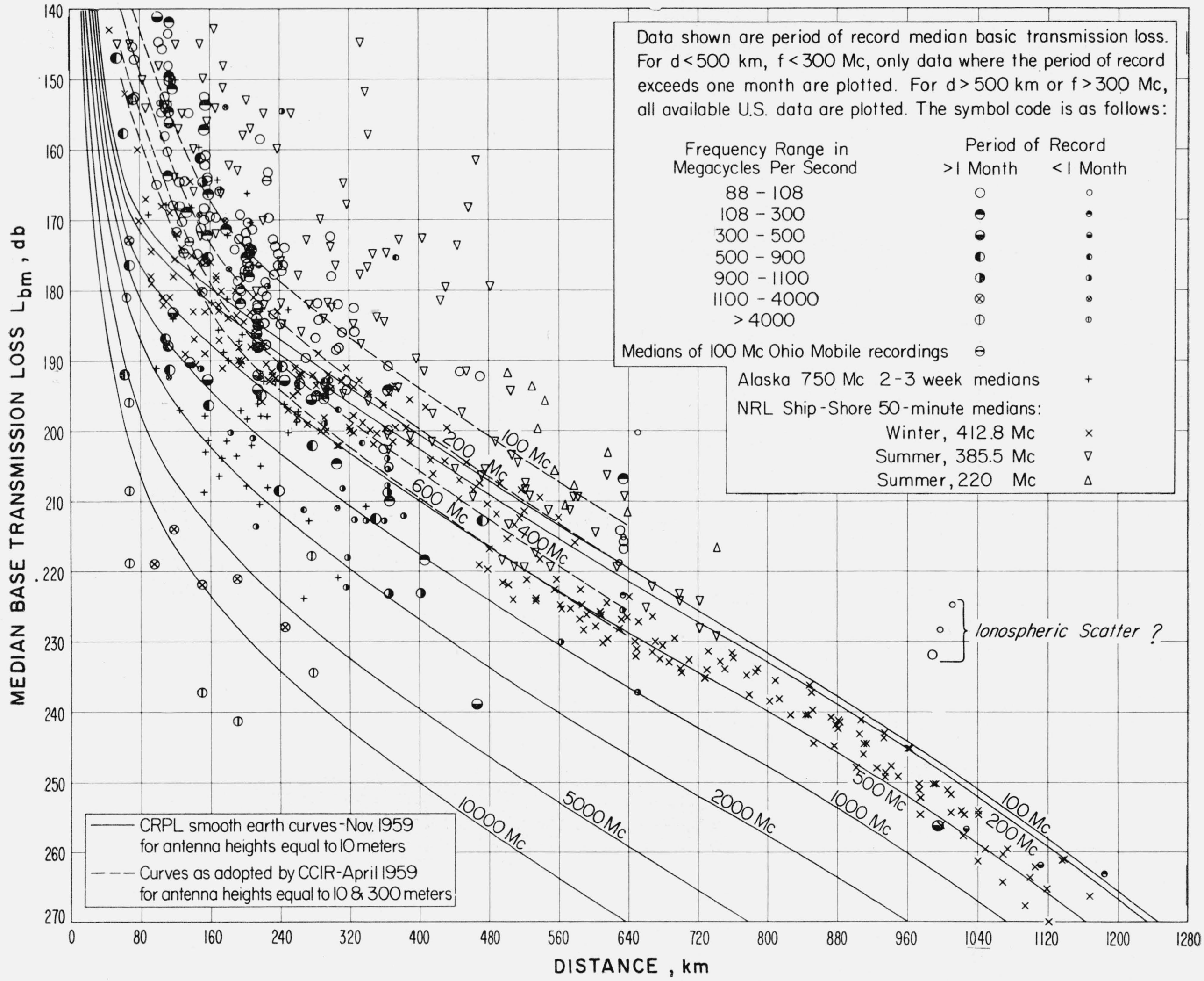

FIGURE 3. *Beyond horizon transmission.*

9. Radio Corporation of America, RCA Review, September 1958.

10. Page Engineers Interim Report P.C.E.-R-4378, May 1957.

11. Syracuse University Technical Reports, EE 312-5511P, Nov. 1955; EE312-5611T3, Nov. 1956; EE12-5711T4, Nov. 1957; and EE312-5810F, October, 1958.

12. Cornell University Research Reports EE229, 1 December 1954 and EE260, 10 Sept. 1955.

13. Additional unpublished data collected by CRPL.

3.2. Effects of Rough Terrain

a. Forward Scattering

Nearly all radio services employ propagation paths in which the electromagnetic waves are transmitted along an irregular, inhomogeneous ground boundary for at least part, if not all, of the transmission path. The result of this influence is manifest in spatial variations in transmission loss. Electrical ground constants, reflection, diffraction, and absorption are all important in varying degrees. Conductivity plays the most important role in the lower frequency ranges below roughly 30 Mc/s, while reflection, diffraction, and absorption become relatively more important at higher frequencies. In any given case the transmission loss at any instant of time is a result of several causes and effects which are exceedingly complex to predict.

Since the XIIth General Assembly held in August and September 1957, most of the work in the U.S.A. involving irregular terrain propagation has dealt with the prediction of VHF and UHF broadcast service fields and the effect of large obstacles producing knife-edge diffraction on point-to-point propagation paths.

The Television Allocations Study Organization carried out studies in 1957 to 1959 of all technical phases of television broadcasting [TASO, 1959]. A large amount of propagation data was obtained representative of television signals transmitted over irregular terrain at both VHF and UHF. New

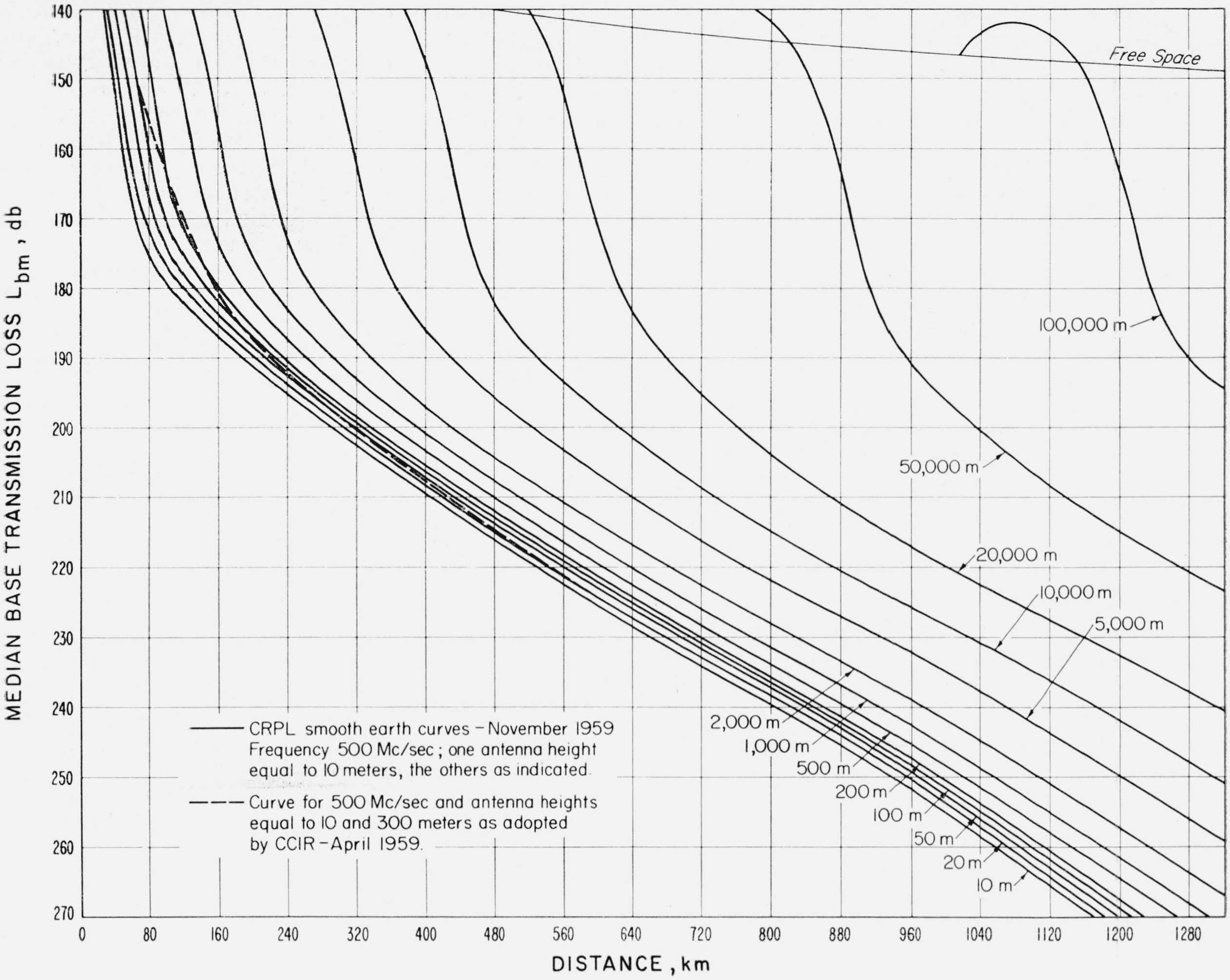

FIGURE 4. *Theoretical smooth earth curves.*

methods of specifying the coverage of a television station are discussed. These methods take the variability of the signal propagated over irregular terrain into account in terms of the statistical probability of receiving the signal throughout various areas surrounding the transmitter.

LaGrone [1959] has developed a new method for predicting the median transmission loss as well as departures from the median expected over irregular terrain paths typical of television transmission paths. His method is largely empirical and is based on the data collected by TASO and on diffraction theory.

Study Group 5 of CCIR [CCIR, 1959] adopted a report concerning the measurement and description of service fields for television broadcasting at the IXth Plenary Assembly held in Los Angeles in April 1959. This work gives a method for describing the coverage of broadcast services in terms of the probability of receiving service in the area surrounding the transmitting station. This paper also presents a statistically efficient method for measuring or estimating the coverage.

Egli [1957] has analyzed irregular terrain propagation data for various low- and high-transmitting and receiving-antenna heights. He has prepared curves and nomograms which should be useful in systems engineering for services affected by irregular terrain, such as land mobile and point-to-point services.

The obstacle-gain phenomenon associated with knife-edge diffraction over a large obstacle has been under further study by both U.S.A. and Canadian investigators. Neugebauer and Bachynski [1958] of Canada have developed a relatively simple method for solving the special case of diffraction over a smooth cylindrical surface. This solution is based on the assumption that the radiating aperture is illuminated by both direct rays and by rays reflected from the illuminated side of the obstacle. The subsequent radiation is also reflected from the shadow side of the obstacle. Although their procedure is not rigorous, it does lead to results which are in good agreement with observations. Wait and Conda [1959e] have developed a method for computing the fields diffracted by convex surfaces which is both rigorous and easy to apply.

A significant contribution to the problem of ground reflections has been made in the field of air-ground propagation. McGavin and Maloney [1959] made an experimental determination of the reflection coefficient over rough terrain using various terminal heights. They separated the specular from the random component and found a terminal height above which the specular component became insignificant. Beard and Katz [1957] found a qualitative relationship between the spectrum of the forward scattered total field and the apparent ocean roughness and the ocean wave spectrum. Wait [1959f] has extensively studied the reflection of electromagnetic waves from a perfectly conducting plane surface which has a uniform distribution of hemispherical bosses with arbitrary electrical constants. He also considers the effect of curvature and of two parallel rough surfaces. These models are expected to be useful in explaining certain experimental data on the terrestrial propagation of VLF radio waves.

Trolese and Anderson [1958] describe an experimental study of the influence of the shape of foreground terrain profiles near terminals of UHF links on the received field. Shkarofsky, Neugebauer, and Bachynski [1958] extend the theory of propagation over mountains with smooth crests presented by Neugebauer and Bachynski [1958] and present the results in a form more suitable for practical applications.

b. Backscattering

Most of the experimental work on radar backscattering has been achieved using airborne radar. Macdonald [1959] has reported on measurements of terrain reflectivity at 425, 1,250, 330, and 9,300 Mc/s with horizontal, vertical, and cross polarization at depression angles of 10 to 90 deg. Measurements were obtained for forest, desert, city, and water surfaces. All targets except the city were found to be "homogeneous" radarwise and the amplitude data showed approximately a Rayleigh distribution at all depression angles.

At the University of New Mexico [Edison, 1959] measurements at 415 and 3,800 Mc/s have been made at depression angles from 60 to 80 deg over farmland, forests, city areas, desert, water surfaces, and some areas with snow and ice cover. The radar return is interpreted as consisting of a scattered component and a specular component, the latter present only at normal incidence. Specular reflection is significant only for very smooth surfaces, such as water and sandy desert. Radar cross sections per unit area, σ_0, sometimes called the scattering coefficient, range at vertical incidence from about 0.5 for forest to 18 for farmland and some city targets. They decrease rapidly with angle for smooth surfaces (for water $\sigma_0=50$ at 415 Mc/s, 200 at 3,800 Mc/s) and slowly for forests. If the ground were a lossless isotropic scatterer the radar cross section per unit area would be 2 at vertical incidence.

Measurements of return from highly uniform terrain such as grass, farm crops, concrete, and asphalt have been obtained at Ohio State University [Taylor, 1959] using 3, 1.2, and 0.86-cm radiation. The effects of polarization, surface roughness, rain, and snow on the results have been investigated.

The spectra of backscattered energy from the sea surface have been investigated experimentally at the University of Illinois [Hicks, 1958] using an airborne coherent 3-cm radar. The sea clutter spectra are found to be proportional to the probability distributions of the scatterer velocities on the sea surface. Theoretical calculations indicate that less than one-half of the average width of the clutter spectrum can be attributed to the orbital particle velocity of the waves while, presumably, surface drift and white-cap velocities contribute the other one-half or more. Higher sea states produce asymmetric spectra and also an irregular downwind broadening of the spectrum.

3.3. Angular Diversity

Experiments in beyond-the-horizon propagation conducted since August 1957 have reemphasized angle of arrival experiments [Staras, 1958]. The basic experiment consists of probing the atmosphere with a single movable beam—the principal advances being the narrowness of the beam and in the speed with which it is scanned. The results of this research can be applied to multiple-feed diversity systems where multiple feeds are placed near the focal point of one large parabolic reflector. The multiple beams can be used simultaneously. Significant research along these lines is exemplified by the five programs summarized below.

At the Bell Telephone Laboratories, Kummer conducted experiments at 4,110 Mc/s and 460 Mc/s, transmitting over a 171-mile path with relatively broad beams and receiving on various narrow beams—down to 0.3° at the higher frequency. By scanning the narrow beam, variations in angle of arrival were apparent, and an average beam broadening was observed. In employing a double-feed and simple-switching diversity, the diversity improvement expected for nearly independent Rayleigh distributed signals was realized at 4,110 Mc/s for both horizontal and vertical angular-beam separation. At 460 Mc/s, this improvement was realized for vertically displaced beams, but for horizontal it varied with fading rate.

At Stanford University, Waterman employed a phased array to receive signals from a 101-mile-distant broad-beam transmitter [Waterman, 1958a, 1960; Miller, 1958]. Rapid control of the phasing permitted a 0.5° beam to be swung in azimuth through a 4-deg sector at the rate of ten times per second—faster than most atmospheric variations. This technique provided a detailed picture of instant-to-instant angle-of-arrival changes and structure. Significant results indicated a finite number of reflecting facets, as if from a rippling layer, that moved around rapidly, in marked contrast to the random scattering anticipated from turbulence theory. The possibility of searching for or tracking a single arriving component was suggested as an alternative to a fixed-beam diversity system.

The Avco Corp. [1958] performed rapid beam swinging experiments at 500 Mc/s over a 50-mile path. A 10-deg beam was scanned electronically at 50-cycle rate. Rapid variations and occasional multiplicities in the angle of arrival were observed.

At MIT-Lincoln Laboratory, the correlation was measured between two beams provided by a dual feed arrangement at a frequency of 2,290 Mc/s and a path length of 188 miles [Chisholm, 1959]. Observed correlations well below unity indicated a substantial diversity improvement for appropriate beam separations.

At Cornell University, Bolgiano, Bryant, and Gordon [1958c] investigated the improvements to be expected from angular diversity systems. Theoretical models were compared with previously obtained Stanford data.

At Rome Air Development Center, Vogelman, Ryerson, and Bickelhaupt [1959] made measurements over a 200-mile path at 8,000 Mc/s of the correlation between 0.3° beams separated in azimuth and elevation. From the extremely low correlations obtained rather elaborate multiple-beam diversity systems were designed.

3.4. Frequency Diversity

The variation of the amplitude of a signal with frequency determines the bandwidth limitations imposed by the propagation mechanism. Experiments consisting of sweeping a frequency many times faster than the fading rate of the signal over a 20-Mc/s frequency band were performed to provide information concerning the "instantaneous bandwidth" of a tropospheric signal [Chisholm, 1958]. These measurements also inherently contained data applicable to frequency-diversity techniques.

Earlier frequency-sweep measurements at 2,290 Mc/s which were reported at the XIIth General Assembly in Boulder were continued [Chisholm, 1959]. These measurements, made over a 188 mile path, provided data indicating the variation of amplitude simultaneously in both time and frequency. Analysis of the results indicated that the correlation of the envelope was 0.5 at 2 Mc/s separation and less than 0.1 at 4 Mc/s. The average instantaneous bandwidth was 3.2 Mc/s.

Similar frequency-sweep measurements at 4,110 Mc/s over a 177-mile path and employing antennas ranging in diameter from 8′ to 60′ [Kummer, 1959] gave results which were in fair agreement with the 2,290 Mc/s measurements. These measurements, however, showed no dependence of the instantaneous frequency variation on the size of the antenna employed.

Preliminary results of reception of 900 Mc/s [Abraham, 1959] FM signals received on two separated sidebands over a 135-mile path were also reported. These measurements indicated the correlation was about 0.5 at 2-Mc/s separation, the experimental limit.

A paper was also presented [Landauer, 1959] reporting a sweep experiment over a 500-Mc/s band, from 3,100 to 3,600 Mc/s. The results of these measurements are difficult to evaluate in the same terms as the other frequency-sweep experiment because of the resolution of the equipment and the slow-sweep rate. These measurements did indicate several peaks of amplitude across this 500-Mc/s frequency band.

The results of all these measured are applicable to modulation and to diversity techniques.

3.5. Diversity Improvement

The objective of any diversity system is to produce two or more channels for transmitting the same information so that the fading on the several channels is essentially uncorrelated. A comprehensive theoretical treatment of the various methods for combining such signals to achieve a signal-to-noise-ratio improvement has been given by Brennan [1959]. He designates the three principal diversity systems as selection, maximal ratio, and equal gain, and shows that the third is the simplest and will generally yield performance essentially equivalent to the maximum obtainable. His principal results are the average SNR improvement and the distribution curves for 2, 3, 4, 6, and 8 channels, with Rayleigh fading and equal SNR assumed for the individual channels. He shows that two signals may be considered uncorrelated when the cross-correlation coefficient $\rho \leq 0.3$, and that significant diversity improvement results even when $\rho = 0.8$.

The most commonly used method for achieving several channels with uncorrelated fading is horizontal space diversity. Recent experimental results with dual diversity, frequency modulation, and maximal-ratio, post-detection combining have been reported by Wright [1960]. The frequency was in the 1,000-Mc/s range. Results include fade-duration distribution without diversity and with dual diversity and comparison with theoretical analysis, as well as total fade duration as a function of depth of fade. The antenna spacing was sufficient to produce cross-correlation coefficients less than 0.3. These data have important applications in the prediction of error rates as a function of median signal level in data transmission.

Recent trends toward the use of larger antennas and higher frequencies have led to the consideration of angular space diversity. With increasing aperture and frequency, the antenna beam becomes so narrow that the available scattering volume in the troposphere is poorly utilized, and "antenna-to-medium coupling loss" may become large. To offset this effect, multiple feeds may be mounted near the focus of a parabolic reflector so as to produce a multiplicity of beams, each of which illuminates a different portion of the scattering volume. In this way, a number of channels is produced which have suitably low correlation coefficients. However, the median SNR's are no longer the same for all channels. The method leads to economy in the use of large reflectors and permits individual transmitters of moderate power to be connected to separate feeders if they operate on separate but closely spaced frequencies.

A beam-swinging experiment, in which a broad transmitting beam and a narrow receiving beam were employed, has been reported by Stanford University [Waterman, 1958b]. Experimental data and analysis of improvement obtained at UHF and higher frequencies have been reported by Bell Telephone Laboratories [Crawford, 1959] and Lincoln Laboratory. Data and computations for a multiple-feed system have been described by the Rome Air Development Center [Vogelman, 1959]. A theorectical analysis of problem has been made by Cornell University [Bolgiano, 1958c].

It is recognized that the uncorrelated channels required for diversity may also be obtained by the use of several frequencies sufficiently spaced from each other. This method seems best adapted for application at the higher frequencies, where spectrum space is currently not too critical. Offsetting extravagant use of spectrum is the fact that only a single feed is required and the several median SNR's are essentially equal.

Some information on the relation between channel spacing and cross-correlation coefficient is available as a result of swept-frequency experiments [Crawford, 1959]. Lincoln Laboratory [Chisholm, 1959] reports a correlation coefficient of 0.1 to 0.2 with a frequency spacing of 4 Mc/s. Airborne Instruments Laboratory reports an experiment in which the frequency was swept from 3,100 to 3,600 Mc/s on a 190-mile path in France, and in which there were at times privileged frequencies on which the signal was 10 db above the median for the band. General Electric Research Laboratory reports analyses of propagation at 915 Mc/s over 135-mile path showing a mean-correlation coefficient of 0.5 for a 2-Mc/s frequency spacing.

3.6. Phase Stability

The measurements of phase stability of radio signals propagated over line-of-sight tropospheric paths have been extended during the past three years. This work was originally undertaken to assist in evaluating the limitations imposed by atmospheric turbulence on direction finding and guidance systems [Herbstreit, 1955]. It has subsequently been expanded to provide basic contributions to our knowledge of turbulence [Thompson, 1960a], in general, and to include other engineering applications such as electronic distance measuring techniques [Thompson, 1958a, 1960b].

The original experiments conducted by the National Bureau of Standards in the Pike's Peak area of Colorado (and later extended to the Maui, Hawaii area) were continued to include paths from about 600 m to 16 km in length, near Boulder, Colo. Effects of antenna size, polarization, radiofrequency and ground reflection were investigated. Measurements were also made over 8- and 15-km paths in Florida on the Atlantic Coast. In all cases the antenna heights were from 1 to 15 m above ground. Supplementary measurements were made of temperature, humidity, barometric pressure, wind velocity, solar radiation, and radio refractive index. The index variations and the phase and amplitude variations of the radio signals were recorded from essentially dc up to 10 c/s spectral components using a 12 channel analog magnetic tape system. Most of the recordings were continuous over 40 hr periods and one was uninterrupted for about 120 hr.

The terrain of the various paths included a very flat ground surface, irregular terrain, and paths over dense vegetation and water surfaces. Weather conditions included calm, clear weather, a cold front passage, snow and cold weather, high winds, heavy rainfall and fog. The experiments were conducted during all four seasons in Colorado and during late summer and fall in Florida [Thompson, 1959a].

The data were analyzed for frequency spectral distribution and for correlation between phase and refractive index measurements. Correlations as high as 0.92 were obtained using a 30-min sampling period. The refractive index-frequency spectra were extended to 10^{-8}c/s ($<$1 cycle per year) through the use of U.S. Weather Bureau data. In the region between about 2×10^{-5}c/s ($\sim$2 cycles per day) and 5 c/s the refractive index and phase variations had slopes of -1.6 and -2.6, respectively, the former closely approximating the $-5/3$ value which has been found to describe the turbulence of horizontal wind velocities.

The power spectra of phase and refractive index were observed to converge at about 10^{-5}c/s (1 cycle per day). For components between this frequency and 3×10^{-8} c/s (1 cycle per year) the slope appears to be about 1.0.

These results are interpreted to have the following significance:

1. Phase fluctuations are significantly correlated with index variations on a time scale consistent with the path length.
2. For many purposes, the variations of both phase and index can best be described by the slope and intensity of their frequency spectra.
3. The most significant changes in these spectra with time appear to be in the intensity, the slopes remaining relatively unchanged.
4. Sufficient data have been obtained at this time to permit reasonably accurate estimates of the phase stability of line-of-sight tropospheric paths from knowledge of their general terrain characteristics and meteorology.

4. Radio Meteorology

4.1. Climatic Investigations

Radio meteorological investigations on the climatic scale involve the physical structure of the atmosphere and have been reported above under topic 1, Physical Characteristics of the Troposphere.

4.2. Refractometer Investigations

Efforts have continued since the XIIth General Assembly to expand our knowledge of the general refractive structure of the troposphere and lower stratosphere by means of direct observations with airborne microwave refractometers as reported under topic 1, 2. Additional refractometer radiometeorological studies have included microscale refractive index measurements to altitudes of about 50,000 ft [Ament, 1957; Bauer, 1958b; Ringwalt, 1957], measurements of the horizontal and time variations in refractive index profiles over distances of 10 to 200 miles and periods of 8 hr [Ament, 1959b], investigations of medium fine scale (several feet) variations in the refractive structure of horizontally stratified layers [Ament, 1959a], correlations of refractive index fluctuations with temperature-lapse rates and wind shear, development of multiple sampling units for aircraft measurements using spaced resonators along orthogonal axes, development of expendable and light-weight refractometers suitable for balloon-borne profile measurements [Deam, 1958, 1959a]. A new type refractometer operating at 400 mc/s and using the stabilized oscillator—beat-frequency principle has obtained profile data in initial balloon borne tests up to 30,000-ft altitude [Deam, 1959b, c], simultaneous measurements in the trade wind inversion of the Central Atlantic of refractive index, temperature, dew point, wind speed, and wind direction [Purves, 1959], extensive measurements of the refractive structure and other meteorological parameters of cumulus and other type clouds, miniaturization and refinement of airborne equipment [Thompson, 1958b], and the development of extremely stable cavity resonators [Crain, 1957a; Thompson, 1958c, 1959b].

4.3. Refraction

Research in this area has followed two general patterns: (a) Calculation of refraction effects from diverse observed refractive index profiles and prediction of refraction effects from statistical consideration of the results [Fannin, 1957; Bean, 1957a]; or (b) assumption of various mathematical models of refractive index structure, calculation of refraction effects in these models and comparison of these effects with those evaluated from observed refractive index distributions [Anderson, 1958; Millman, 1958a, b; Wong, 1958; Bean, 1959d]. Significant results are: (a) The tropospheric component of elevation angle error or the total tropospheric bending of radio rays may be predicted to a high degree of certainty from the initial or ground level value of the refractive index for initial elevation angles as small as 3 deg [Fannin, 1957; Bean, 1957a] and reasonably well for elevation angles down to zero with the additional knowledge of the initial refractive index gradient [Bean, 1959d]. (b) The normal decrease of the refractive index with height in the troposphere is better described by an exponential function than by the linear decrease assumed by the effective earth's radius theory and the exponential model atmospheres yield more reliable estimates of refraction effects [Anderson, 1958; Bean, 1959d]. (c) The rate of decrease of refractive index with height in the atmosphere varies with geographic location and season of the year and the tropospheric part of this variation may be specified reasonably well from knowledge of the ground level value of the refractive index alone [Anderson, 1958; Bean, 1959d]. (d) From consideration of the above, the Plenary Assembly of the CCIR (Los Angeles, April, 1959) recommended for international use a basic reference atmosphere based upon an exponential model of the refractive index. Further, these studies have reemphasized the importance of the lowermost layers of the atmosphere since about one-third of the atmospheric bending of a ray leaving the earth tangentially, and passing completely through the troposphere and stratosphere, occurs in the first few hundred meters above the ground.

An important experimental investigation of tropospheric refraction effects utilizing radars [Anderson, 1959] indicates that refraction errors can be an order of magnitude greater than instrumental error for initial angles of 1 deg. Good agreement was obtained between observed and calculated elevation angles with the conclusion that the degree to which radar may be used with accuracy is directly dependent upon the availability of meteorological data.

Simplified methods have been developed [Weisbrod, 1959] which allow one to readily determine from routine radiosonde and ionogram data ray bending and retardation, as well as elevation angle error, Faraday rotation, and Doppler error caused by both the troposphere and by ionospheric layers.

Consideration of departures of atmospheric refractive index structure from the commonly assumed horizontally stratified condition indicates that such departures can significantly affect the refraction of radio rays [Wong, 1958; Bean, 1959e] but that significant departures do not commonly occur more than 20 percent of the time at most locations so that the majority of ray path calculation may be carried out under the normal assumption of horizontal stratification of the refractive index.

4.4. Radar Meteorology

The use of radar in weather analysis and forecasting is now on an operational basis in many areas and new techniques are constantly being developed for its employment as a research tool. Recent and quite comprehensive bibliographies have been published on radar meteorology [Thuronyi, 1958] and on thunderstorm sferics [Thuronyi, 1959].

The largest outlets for the presentation of research in this field are the Weather Radar Conferences, the Proceedings of which have been published by the American Meteorological Society. Specific references to the Seventh Conference are included here. In a Conference on Hurricanes held at Miami Beach, the very complex radar instrumentation of hurricane reconnaissance aircraft was described [Hillary, 1958; Hurt, 1958]. Detailed studies of specific storms have shown that echoes can be obtained not only from precipitation bands but from sea and swell as well [Trupi, 1958]. A comprehensive analysis of hurricane spiral bands by radar has resulted in new data concerning their origin and growth [Senn, 1958].

In the larger scale employment of radar, efforts have been made to combine visual and radar return from clouds with the existing synoptic pattern [Boucher, 1959; Wilk, 1958] and to demonstrate the successful forecasting technique of combining the returns from several radars to give echo patterns on a synoptic scale [Ligda, 1958b]. By associating precipitation echoes with liquid water content, it has been shown that radar can be used effectively to study the distribution of three dimensional winds in the atmosphere [Kessler, 1958]. Some of the most striking applications of radar data can be found in analyses which have associated the detailed echo structure, growth and movement with the meso- and microscale pressure and wind patterns of hail producing thunderstorms, tornadoes and squall lines [Donaldson, 1958, 1959; Fujita, 1958a, b, 1959; Inman, 1958; Tepper, 1959]. A new Doppler radar has been developed which can be used to study the rotation characteristics of tornadoes [Holmes, 1958].

Recent studies have been made which show the growth and development of precipitation cells within storm areas [Douglas, 1957; Wexler, 1959], which discriminate between condensation-coalescence and ice crystal produced precipitation [MacCready, 1958], and which show the relationship between drop size distributions and the types of precipitation layer echoes observed [Hunsucker, 1958]. Other applications include analyses of the fluctuating nature of radar return to deduce properties of the field of turbulence within the illuminated atmosphere [Stackpole, 1958] and the exploration of such phenomena as sferics, lightning, and auroras [Atlas, 1958; Rumi, 1957].

The controversy relating to the explanation of angel-type echoes continues unabated. The radar ornithologists have given strong documentation to their viewpoints [Harper, 1958; Richardson, 1958], but the fact remains that echoes have been observed from convective phenomena and frontal systems [Atlas, 1959; Ligda, 1958a] whose only reasonable explanation lies in their associated variations of refractive index. Laboratory tests, on the other hand, have shown that gradients are probably not responsible for echoes at millimeter wavelengths [Tolbert, 1958]. An excellent bibliography has been published [Plank, 1956].

Certain applications are being found for climatological aspects of radar return data, including area precipitation averages [Beckwith, 1958] and model reflectivity-altitude contours [Atlas, 1957]. The use of radar echo patterns to obtain quantitative rainfall-area amounts is well established [Hiser, 1958]. Another technique now in operational use is that of the automatic production of constant altitude PPI(CAPPI) cross sections. These have been found to be extremely useful in short range forecasting and research [Boucher, 1958].

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