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A Radiometeorological Study, Part I. Existing Radiometeorological Parameters

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A survey is made of existing radiometeorological parameters, including those derived from the vertical profile of refractive index, n, and others which involve the concept of thermal stability. Quantitative comparison of radio and meteorological data confirm the value of N_s (the surface value of $[n-1]10^6$) and ΔN (the difference in value of N_s and N at one kilometer) in a wide variety of conditions. For particular areas, however, it seems desirable to develop improved prediction techniques using a parameter which is related to the size, stability, and intensity of elevated layers in the troposhere.

1. Introduction

A method of predicting the statistical distribution of field strength on transhorizon paths is an important requirement in tropospheric wave propagation. Consequently, considerable attention has been given in recent years to studies of the correlation between the measured signal level (e.g., the monthly median value) and some quantity derived from surface or upper air meteorological data. If a reliable "radiometeorological parameter" could be developed then generally available meteorological data would replace expensive radio measurements in deriving the required distribution.

Considerable progress has already been made in this difficult problem by workers at the National Bureau of Standards, Boulder Laboratories [Bean and Meaney, 1955; Bean and Cahoon, 1961]. In these investigations, special attention has been given to two parameters: (a) the surface value, N_s, of $(n-1)10^6$, where n=refractive index, and (b) the difference, ΔN, between N_s and N_1 where N_1 is the value of $(n-1)10^6$ at a height of 1 km. Other groups have studied different parameters [Misme 1960a, b, and c; Flavell and Lane, 1962; Moler and Arvola, 1956; Moler and Holden, 1960], either as possible alternatives to N_s and ΔN in the prediction process or as quantities which clarify the effect of meteorological features, such as anticyclonic subsidence, on signal strength. It is evident from the literature that some difference of emphasis exists regarding the relative merits of the parameters proposed to date, and particularly on the value of studies of N_s. The purpose of these papers, therefore, is to provide a critical survey of the present position in this field of radiometeorology and to indicate a new approach which incorporates some aspects of all existing treatments. Part I contains a study of previous work and attempts to put the various views in proper perspective; part II discusses some selected radio data from VHF paths and its classification in terms of refractive index profiles, while part III introduces a parameter combining properties of refraction and atmospheric stability and compares correlations obtained with this new parameter with those obtained with existing parameters.

The development of prediction techniques is especially difficult in the case of:

(a) any path with terminals in the vicinity of the normal radio horizon

(b) signal enhancements which occur well beyond the radio horizon for small percentages of the time.

Very little data are available for (a), therefore part II includes some discussion of propagation characteristics on VHF paths that are well beyond the horizon, for which considerable radio and meteorological data are available. The results obtained are particularly relevant to an understanding of the large differences observed between median signal levels on VHF paths of comparable length, frequency, and angular distance.

The primary purpose of a radiometeorological parameter is to provide the best estimate of the statistical distribution of transmission loss (in terms of hourly, daily, weekly, or monthly median values as required on a specific path). The reliability of the parameter must be judged solely in terms of this requirement, and care must be exercised in assessing the value of any given parameter in terms of data obtained over limited intervals of time or from restricted geographical areas. Discussions later in the paper will consider to what extent it is possible to develop a parameter which, in addition to being statistically reliable, is also characteristic of the physical structure of the atmosphere.

The present practice in applying radiometeorological parameters consists of determining an average signal level for a given path and then adjusting this average level for climatic and seasonal differences by reference to the changes in some function of the refractive index of the atmosphere. We may express this procedure as a linear regression model,

$$E=b\cdot f(n)+a$$

where E is the field strength, and b is the regression coefficient expressing the sensitivity of E to a unit change in $f(n)$. The intercept, a, is a function of path length, antenna heights, and terrain characteristics, and in this paper is estimated from existing prediction procedures [Rice, Longley, and Norton, 1959]. Comments on some results obtained are given in the remainder of this paper.

2. Parameters Derived From the N-Profile

It has long been recognized that the variations in transmission loss on transhorizon paths are correlated with changes in the vertical gradient of refractive index over the path. Although our knowledge of the detailed fluctuations in refractive index in the troposphere is still inadequate for many requirements, it is nevertheless possible to relate statistically changes in signal level and functions of a parameter derived from routine surface and upper-air measurements of pressure, temperature and humidity.

2.1. N_s and ΔN

Following the work of Pickard and Stetson [1950], N_s and ΔN have been the subject of detailed studies by several workers [Bean and Meaney, 1955; Bean and Cahoon, 1961; Bonavoglia, 1958; Gray, 1961; Onoe, Hirai, and Niwa, 1958; Bean, Fehlhaber, and Grosskopf, 1962]. Some of the conclusions are summarized here. Values of the correlation coefficent, r, relating monthly median values of either N_s or ΔN and field strength, derived from a number of paths in diverse climatic conditions, [Bean and Cahoon, 1961] range from 0.4 to 0.95 with a median value of about 0.7. An analysis has also been made of the results obtained by using (a) values of ΔN obtained from the surface readings and at heights other than 1 km and (b) values of ΔN between different levels on the profile up to a height of 3 km. A comparison of measured field strength at frequencies near 100 Mc/s on 20 paths, 130 to 446 km long, located in various parts of the United States, yields the following result: the use of N_s gives as good a correlation as any of the ΔN values, due to the high correlation between the surface value and these differences. The values of r relating monthly median values of N_s and ΔN (the decrease in the first kilometer) have been obtained for the United States, [Bean and Thayer, 1959], France, [Misme, 1958], Germany, [Bean, 1962], and the British Isles, [Lane, 1961]; they range from 0.60 to 0.93. Moreover, the data are consistent with the assumption of a reference atmosphere in which N decreases exponentially with height [Bean and Thayer, 1959]. These results lead at once to a consideration of the value of N_s in predicting the geographical variation of monthly median field strength, and this question is considered in more detail in section 4.

It has been shown that, where only past radio or meteorological results are available, one obtains at least as good a prediction of the diurnal and seasonal variations of field strength from long-term meteorological data as from relatively short-term (say 1 year's) radio data. The annual cycle may be represented by a single regression coefficient of 0.18 db per N-unit (0.18 db/N_s) for either night or day; however, the regression coefficients for the diurnal cycles lie between 0.2 and 1.1 db/N unit and vary with path and season, being greatest for paths between 175 and 200 km long and for the winter months. The possibility of predicting the variation of hourly median values of field strength within any given month by combining the seasonal and diurnal correlations has also been discussed [Bean, Fehlhaber, and Grosskopf, 1962]. It is recognized that the development of a prediction procedure based on this approach must account for the complex sensitivity of field strength, E, to changes in N_s; this requirement in turn leads to considerations of season, climatic region, distance and frequency. The results for the distance dependence of the E–N_s regression coefficient are, of course, intimately connected with the propagation mechanism. In particular, in the case of VHF paths about 200 km long there will be components in the received field due to diffraction around the earth's surface and scattering from randomly dispersed eddies; on occasions there will also be a semicoherent field arising from partial reflection at elevated stable layers. Some aspects of this complex situation are discussed in part II of this work.

To sum up other conclusions reached by the authors mentioned above, the correlation between E and N_s

(1) increases with increasing variation of E or N_s,

(2) is greater for seasonal cycles of nighttime values of the variables than for the midday values,

(3) is greater for summer diurnal cycles than for winter ones.

Conclusions (1) and (2) are particularly important if we try to assess the utility of N_s in prediction work in terms of signal data from areas in which the variation of E is small (e.g., Western Europe), or in terms of data for afternoon periods only.

2.2. Equivalent Gradient, g_e

Another parameter, closely related to ΔN, is the "equivalent gradient," g_e, proposed by Misme [1960]. This is defined as that linear decrease of n with height which produces the same amount of bending as the actual inhomogeneous atmosphere over a given transmission path. The problem is illustrated in figure 1, where the dotted line represents the actual ray path between T and P above an earth of radius a. It is required to determine the curvature, ρ, of the circular, full-line path which is tangential to the real path at P and which corresponds to a constant value of dn/dh in a fictitious atmosphere. Boithais and Misme [1962] have described a graphical method for calculating $g_e(=1/\rho)$, for example when P is located in the center of the common volume of the antenna beams. Monthly median values of g_e are obtained from the corresponding monthly median values of dn/dh, and Misme [1960] has given tables of g_e for various path lengths for different months.

It is evident that g_e, like ΔN, expresses the amount of refraction produced by the atmosphere and one might expect a high correlation between the two

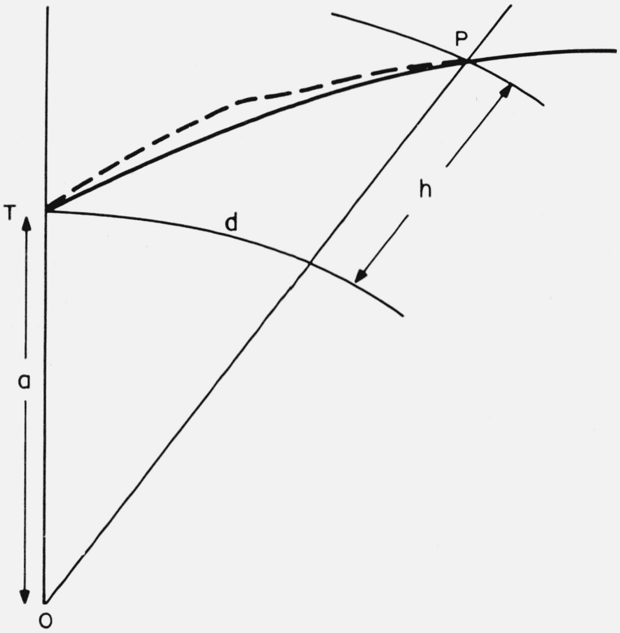

FIGURE 1. *Derivation of equivalant gradient.*

parameters. This is known to be the case in some results quoted by Misme [1960] and which are illustrated in figure 2. Here the monthly median values of ΔN and g_e (for a 300 km path) are compared, together with the variation in N_s, for Leopoldville in the Congo area. The correlation between g_e and ΔN is high, but the maximum values in N_s in December and January are accompanied by a local minimum in the values of g_e and ΔN. These results, and similar ones from Dakar (W. Africa), have been quoted in support of arguments that N_s is of limited value in predicting seasonal and geographical variations in field strength [Misme, 1960]. It is essential, Misme claims, to investigate the nature of the $N_s - \Delta N$ correlation in separate climatic areas; the correlation seems poor for some equatorial climates, probably because of the presence of semipermanent elevated layers. In these conditions, Misme feels that an exponential reference atmosphere and a correlation between N_s and ΔN are not to be expected.

While admitting the importance of an explanation of the results discussed above, it is difficult at present to accept the argument that g_e should be used instead of ΔN. Indeed, it has been shown [Misme, 1960] that for a 471 Mc/s link, 160 km long, located in the Sahara region, there is a difference of 20 db between the signal levels exceeded for 99 percent of the time during daylight hours in January and June, whereas the January to June variation in g_e is less than $2N$/km. This result indicates the influence of atmospheric stability on signal strength. We defer, therefore, further consideration of g_e until later in the paper, merely noting at this stage that its derivation requires more detailed calculation (i.e., ray tracing) than in the case of ΔN, without any appreciable benefit.

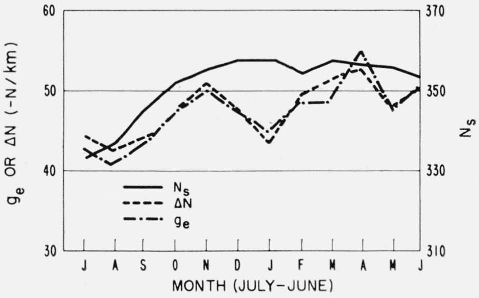

FIGURE 2. *Comparison of monthly medians of g_e, ΔN and N_s.* (Leopoldville, Congo)

3. Parameters Involving Thermal Stability

The role of stable elevated layers in tropospheric propagation has been discussed by a number of workers; for example, by Saxton [1951], Gossard and Anderson [1956], Friis, Crawford, and Hogg [1957], and recently by French workers [du Castel, Misme, Spizzichino, and Voge, 1958–1960] in an important series of papers. These contributions have stimulated interest in the development of radiometeorological parameters which depend, in part at least, on thermal stability, and this section considers some of the characteristics of these parameters.

3.1. Composite Parameter

Misme [1960] has discussed the Sahara results mentioned above in relation to the theoretical work of Voge [1958–1960]. In considering the effect of elevated layers, Voge introduces a parameter η defined by:

$$\eta = \frac{\text{area of one or several layers at a given height}}{\left[\begin{array}{c}\text{the horizontal area, at the same height, visible}\\ \text{from receiver and transmitter}\end{array}\right]}.$$

η is an increasing function of the atmospheric stability measured between two levels in the atmosphere. Stability may be defined as the work, ΔW, required to raise a unit mass of air from one level to another. We have, therefore;

$$\eta \text{ tends to } 0 \text{ as } \Delta W \text{ tends to } 0$$
$$\eta \text{ tends to } 1 \text{ when } \Delta W \text{ is large.}$$

The values of ΔW (in joules per gram) for Aoulef (Sahara) are given by Misme for the January and June months in which measurements were made over the 160 km path at 471 Mc/s. The relevant data are summarized in table 1. The dominant propagation mechanisms in January and June are thought to be "diffuse reflection" and "scattering" respectively, and on this basis Misme uses the equations given by Voge to calculate the expected difference in the January and June signal levels. With various assumptions regarding the properties of stable and turbulent layers, a value of 19 ($\pm$5) db is obtained for the ratio of predicted field strengths in January and June, in good agreement with the measured value exceeded for 99 percent of the time. This analysis is facilitated by the fact that the two selected months are characteristic of well-defined climatic situations in the Sahara region. Nevertheless, the results indicate that a parameter which combines the concepts of the equivalent gradient and thermal stability may be of general application. Misme [1960] has therefore suggested a parameter M of the form:

$$M=a(g_e-40+b[\Delta W]^n) \tag{2}$$

where a, b, and n are constants, g_e is the equivalent gradient, and ΔW is the thermal stability defined above for a 1 km height interval. With $a=0.5$ db/N/km, M provides an estimate of the variation in field strength, E, in decibels, caused by changes in equivalent gradient and stability. It remains to define E in a "standard" atmosphere by selecting a mean value of stability and a suitable value for the term b.

This composite parameter is thought by Misme to be more representative of the real atmosphere (especially in tropical areas) than N_s and ΔN, and it is certainly of great potential value. However, only fragmentary radio data are available for purposes of comparison in the references quoted, and here again the precise value of the parameter in prediction work can only be determined by a more comprehensive study.

TABLE 1. *Influence of thermal stability on signal level*
(d=160 km; f=471 Mc/s; North Sahara region)

	January	June
g_e ($-N$/km)	34	32.5
ΔW for 0.7 to 2 km	0.17	0.0024
Relative signal level, 99% value (db)	20	0

3.2. Potential Refractive Index (or Modulus), K

The K unit may be obtained from the ϕ unit [Craig, 1946; Katz, 1951]. The ϕ unit is defined as the value of $N=(n-1)10^6$, which an air mass would have if brought adiabatically to a standard pressure, assuming a constant humidity mixing ratio. If this pressure is 1000 mb, the ϕ_{1000} unit has been called the K unit [Jehn, 1960]. Examples of the use of both ϕ and K in radiometeorology have been given by Katz [1951], and by Jehn [1960]. The K unit has also been applied by Flavell and Lane [1962] in studies of the effect of anticyclonic subsidence on tropospheric propagation. K values can be derived very rapidly from upper-air data and, since plots of K against height or pressure do not exhibit the large systematic decrease of N with height in the conventional $N(h)$ profile, the structure and motion of meteorological features are clarified considerably. (Below the condensation level, a lapse rate of $-20N$ km$\equiv dK/dh=0$.) In this respect, K is superficially similar to the "A" unit [Bean, Riggs, and Horn, 1959] derived from the exponential reference atmosphere. However, no quantitative results are yet available with this parameter and, furthermore, the method of deriving K assumes a dry adiabatic lapse rate and a constant humidity mixing ratio. The presence of a condensation level in the actual atmosphere is therefore neglected. In addition, accurate values of N can only be derived directly from the K profile in certain restricted conditions. Pending further studies in this direction, therefore, K and dK/dh remain more suitable for qualitative synoptic studies than for quantitative predictions of field strength variations. However, it is of interest to note that a close connection exists between K and the composite parameter M discussed above. Misme [1962] has shown that the change of K in a given height interval, $\Delta K/\Delta h$, is of the form:

$$\Delta K/\Delta h=k_1(\Delta N/\Delta h-k_2\Delta W/\Delta h) \tag{3}$$

where k_1 and k_2 are constants, and ΔW is a measure of thermal stability as defined in section 3.1.

3.3. Vertical Motion of the Atmosphere

The influence of stability has also been discussed by Moler and Arvola [1956]; Moler and Holden [1960]. These authors assume that the average lapse rate, $\overline{dn/dh}$ and the magnitude of local irregularities on the profile, are primarily determined by changes in vertical velocity. Local centers of convergence (low pressure cells) produce updrafts which result in considerable mixing and the dissipation of any stable layer structure. Horizontal divergence from local high pressure centers create temperature inversions and associated layer-type discontinuities in the n-profile. These latter features are most pronounced in conditions of anticyclonic subsidence.

The direction and relative magnitude of the vertical component of wind velocity can be estimated by techniques outlined by Moler and Holden, and a correlation between hourly median field strength and calculated values of vertical velocity has been noted by these authors. These fundamental studies represent an important attempt to explain signal variations in terms of atmospheric motion, and a survey of available experimental evidence supports the basic assumptions in this approach. It is particularly interesting to consider whether local centers of convergence and divergence, ill-defined on Daily Weather Reports, can be distinguished by observations with microbarographs and whether the results are correlated with signal characteristics. Some results of such an investigation, forming part of a more general study of VHF propagation in the United Kingdom, are shown in figure 3. The signal record obtained at a frequency of 186 Mc/s on a 140 km path are shown for 12 September 1959 together with the pressure variations recorded at transmitting and receiving sites. The steady high signal at 0900 hr begins to fall as the pressure at the transmitter begins to decrease, and at about 1030 hr the median level and fading rate change abruptly as the pressure at the midpoint falls. Between 1200 and 1700 hr the pressure over the whole path is falling, and the

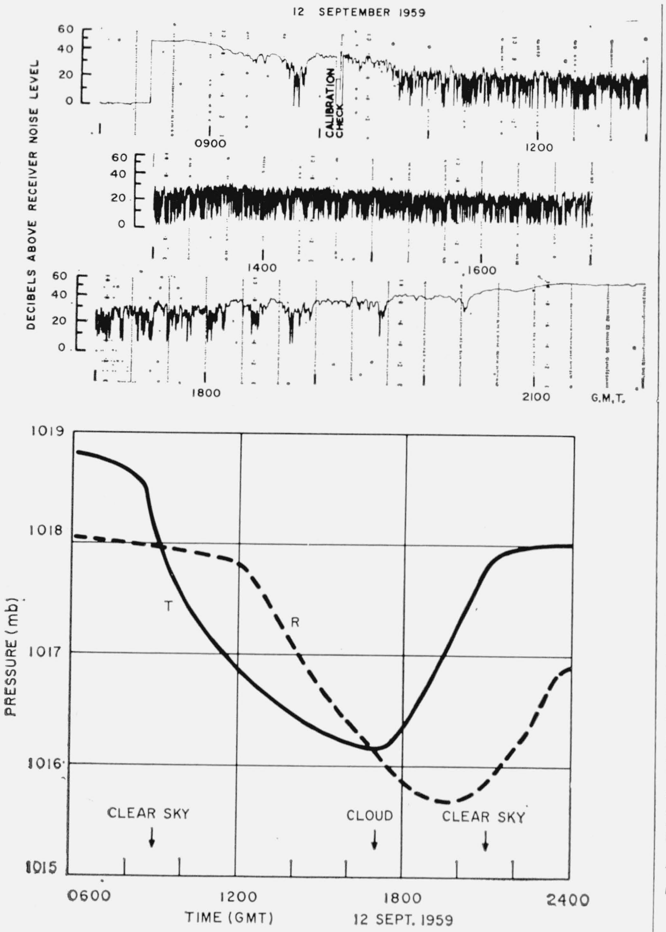

FIGURE 3. *Signal records and pressure variations at transmitter, T, and receiver, R, on 140 km path;* f=*186 Mc/s.*

signal characteristics remain essentially uniform. However, a significant increase in median level and a reduction in fading rate are evident at 1700 hr as the pressure begins to increase at the transmitter. By about 2300 hr the pressure at the center of the path has reached a steady value and the signal level is again high with negligible fading. The total barometric variation between 0900 hr and 2200 hr is only 2mb.

There is obviously a fruitful field of radiometeorological study suggested by the work outlined above, but we have to conclude that the results obtained, while extremely valuable in clarifying a qualitative relationship between signal strength and vertical motion (or stability), are not immediately applicable in the problem of predicting field strength variation.

4. Discussion of the Parameters

The above review emphasizes the need for a critical inspection of representative data, radio and meteorological, with the objective of comparing the merits of the several parameters and explaining, if possible, some of their relative merits and limitations. Some relevant points have been mentioned already in section 2.2, and these issues are developed in more detail in the following discussion.

It is important to bear in mind that in the particular problem of predicting field strength changes we are concerned with a statistical relationship between two quantities, the median signal level and a radiometeorological parameter. It may be advantageous, of course, to investigate the merits of special parameters developed for particular climatic areas; for example, the value of the gradient, dn/dh, in a semipermanent elevated layer in the trade winds area. Nevertheless, such a parameter must also be statistically "reliable" if it is to be applied in prediction analysis.

4.1. Comparison of Some Parameters

It is probably fair to say that, at present, the greatest interest is concentrated on the relative merits of N_s, ΔN, and g_e, for these quantities have received more detailed attention than any others. (It might be argued that, since the initial gradient of refractive index with height has a strong influence on refraction, this quantity should be highly correlated with signal level. However, the errors of measuring the initial gradient by radiosonde techniques effectively mask the correlation with the signal.) In a comparison of N_s, ΔN, and g_e, the monthly median values of transmission loss, L, were determined for the hours of radiosonde ascents for 20 radio paths in various parts of the United States. The equivalent gradient, g_e, was then calculated using standard ray-tracing techniques [Bean and Thayer, 1959] assuming:

(a) the actual antenna heights,
(b) a smooth earth with the sea-level radius,
(c) horizontal stratification of N with a vertical distribution the same as that of the monthly mean.

Standard statistical methods were then employed to determine the correlation between monthly median values of (a) E and g_e, (b) E and N_s, and (c) E and ΔN (surface to 1 km height). The average values of these correlation coefficients for the 20 paths are given in table 2. The paths studied in this comparison were the same as those listed by Bean and Cahoon [1961] in their analysis of N_s-ΔN correlation. The data used were representative of climatic conditions ranging from those of New England and the Great Lakes area to Texas and the Pacific coast. This investigation, at least, would seem to justify existing prediction procedures based on N_s and ΔN. It is valuable, however, to consider some of the results for specific paths in more detail, since they illustrate some features of interest directly relevant to the arguments concerning the value of N_s and ΔN.

TABLE 2. *Average correlations,* r(z), *of refraction variables with field strength*

(20 paths, 130–446 km long, f=92–106 Mc/s)

Variable	g_e	N_s	ΔN
$r(z)$	0.59	0.70	0.71

4.2. Some Exceptions and Anomalies

In so complex a matter as field strength prediction it would be unreasonable to expect any radiometeorological parameter to be of worldwide application to a uniform degree of reliabliity, and some conditions have already been quoted where N_s may not be a reliable parameter. The significance of these examples is really the issue on which views diverge most at the present time. Unfortunately, adequate radio data are not available for several areas of interest (e.g., equatorial Africa and in these cases we can only propose tentative explanations based on a critical examination of existing results, for similar but not identical conditions.

An examination of available data, in published and unpublished reports, has shown particular examples which deserve further study, such as climatic conditions in which stable elevated layers are persistent during certain seasons of the year. Attention has already been drawn to an example in this category; namely, the path from San Diego to Santa Ana, Calif. [Bean and Cahoon, 1961]. The well-defined coastal inversion in this area occurs at a height of about 0.7 km, and the associated stable layer has a strong influence on radio field strength. Here the correlation between field strength and N gradient for heights up to 0.7 km above the surface is small *and negative* (i.e., opposite to the general trend). The correlations with N_s, however, and with N differences to heights above the base of the inversion, are about 0.8. This result suggests an explanation of some of the results, already mentioned, for Dakar and Leopoldville. Consider the profile of figure 4, typical of ascents made through daytime inversions in equatorial and Mediterranean areas. (For comparison purposes, an exponential reference atmosphere is also shown.) At Dakar, for example, an elevated layer is observed in 40 to 50 percent of the daytime soundings during August, frequently with the base of the inversion above 1 km height. In these conditions, at least, the high N_s values measured in August are not accompanied by high values of ΔN (0 to 1 km),

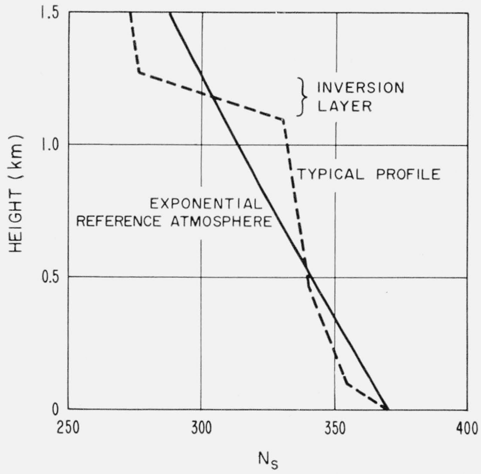

FIGURE 4. *Typical profile through inversion layer (equatorial and Mediterranean areas).*

for the lapse rate, dN/dh, below the inversion is generally less steep than would be expected for the given value of N_s. It would be valuable, therefore, to examine in more detail the distribution of the height of the layer, particularly in the summer months. If the data given by Misme contain an appreciable fraction of such profiles, then the poor $N_s-\Delta N$ correlation he discusses is not surprising. The correlation between N_s and signal level, however, could still be significant, as in the San Diego-Santa Ana link [Bean and Cahoon, 1961]. Further radio data are obviously required for areas in which elevated inversions are persistent.

In many temperate regions, a somewhat different situation exists. In Western Europe, for example, the annual range of monthly median values of N_s is 10 to 20 N units; similarly, the variation in the monthly median values of field strength is also small and frequently lies within the estimated measurement error. Figure 5 shows some results which illustrate these features. Monthly median values of relative field strength are shown for the months January–November 1959, for a 300 km path at a frequency of 174 Mc/s; the terminals being located at Lille (N. France) and Reading (England). The variations in N_s obtained from the Crawley radiosonde station (close to the midpoint of the path) are also shown. N_s has a range of ± 10 N units, and the signal level a range of no more than ± 4.5 db. In fact, from March to September the total variation in observed monthly median field strength is only ± 1.5 db. The measurements of field strength in these experiments were estimated to be subject to possible errors of about ± 3 db. Consequently, one would not be justified in assessing the value of N_s as a radiometeorological parameter on the basis of the correlation coefficient (about 0.25) calculated from the two curves in figure 5. During the period studied in this work (0900–2300 GMT daily, Jan.–Nov. 1959) the highest signals were observed during anticyclonic winter weather, with elevated inversion layers at a height of about 0.6 km. Extended stable layers at this height were rarely seen on the sonde ascents during the summer months. This result may partly explain the fact that the seasonal variation in N_s (highest values in the summer months) is not accompanied on the Lille-Reading path by a corresponding variation in monthly median field strength.

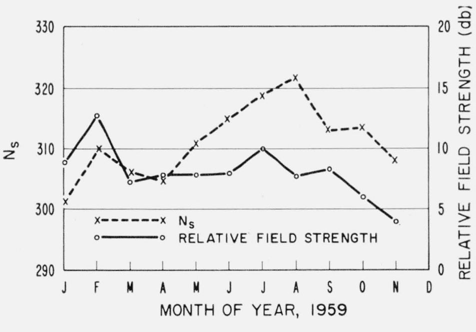

FIGURE 5. *Variation of monthly median values of N. and field strength for 300 km path from Lille (N. France) to Reading (England).*

5. Conclusions

A review of available data shows that no radio-meteorological parameter has yet been proved to be superior to N_s or ΔN for general application in the prediction of field strength distributions. The value of these parameters has been established by studies of many paths in diverse climatic conditions. However, it should be noted that much of the radio data has been obtained at frequencies near 100 Mc/s, and there is a clear need for further analysis of the several parameters in conjunction with field strength measurements at higher frequencies.

Pending more detailed results, it does not seem likely that the equivalent gradient, g_e, affords any significant advantage over ΔN, especially in view of the many calculations required in its derivation. Some data from selected areas (Congo, Sahara, W. Africa) suggest that N_s and ΔN may have limited value in these regions; however, the present lack of adequate radio data precludes any definite conclusions. These examples, and allied work on vertical motion and thermal stability, emphasize the importance of a parameter (such as that suggested by Misme) which takes account of the influence of elevated layers. This approach would probably prove fruitful not only in equatorial areas but also in temperate regions where the annual range of N_s and ΔN is small.

Analysis of some results obtained at a frequency of 100 Mc/s has shown that it has proved feasible to provide at least as good a prediction of the annual cycle of field strength variations from long-term meteorological data as from relatively short term radio data.

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