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Propagation of Radio Waves With Frequency 99.9 Mhz as a Function of the Vertical Structure of the Atmosphere Derived From Daily Radiosonde Observations

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A special parameter was derived from radiosonde observations to indicate the atmospheric structure. The relation between this parameter and the propagation of UHF radio waves beyond the horizon was investigated statistically. It was found that this relation was strong at midnight, but much weaker, though not absent, at noon. As an analogous difference exists between summer and winter data, it is suggested that for abnormal propagation apart from special layers with a large gradient of the refractive index, also, a stable atmosphere in the *lower* levels is required.

1. Introduction

The influence of the atmospheric structure on the propagation of high-frequency radio waves has been an object of active research during the last decade [URSI Congress, 1960]. It is possible to distinguish the following meteorological factors, which affect this propagation [Tao, 1957].

(1) Scattering as a result of atmospheric turbulence. This effect will not be discussed in this paper. It is mainly of importance for propagation over long distances and the material available for the present study refers only to short distances beyond the horizon [Tao, 1957].

(2) Refraction. This process can be subdivided into:

a. Normal refraction, which originates from the gradual vertical variation of the refractive index, and

b. super-refraction and/or reflection, resulting from the atmospheric layers with rapid or almost discontinuous variation of the refractive index with height.

The so-called modified refractive index can, in good approximation, be computed from the following equation [National Bureau of Standards, 1946].

$$N=(n-1)\ 10^6=\frac{80}{T}\ (p+4800\tfrac{e}{T}),\ \text{where}$$

n=refractive index of the atmosphere
N=modified refractive index
p=air pressure in millibars
e=pressure of water vapor
T=temperature of the air in degrees Kelvin.

Strong vertical gradients of the refractive index will therefore occur in cases with a sharp temperature inversion or with a sharp decrease of the vapor pressure. The latter is more important than the former. However, in practice, at our geographic latitude the combined effect of temperature inversion and water vapor lapse is always decisive.

It follows from theoretical considerations that the curvature of the path of the radio waves surpasses that of the earth, when

$$\frac{\delta N}{\delta h}>0.157\ \text{m}^{-1}.$$

The aim of the present study is to investigate how far routine radiosonde observations can be utilized for forecasting the propagation of high frequency radio waves. In other words, an attempt will be made to derive from the radiosonde observations a parameter which is closely connected with the path of the radio waves through the atmosphere.

It should be mentioned that several authors [Spencer, 1952; Arvola, 1957; Maenhout, 1958; Braam, 1960] qualitatively have investigated which synoptic processes are responsible for a certain variation of temperature and humidity and therefore for the variation of the refractive index with height. Although the importance of these studies cannot be denied, due attention should in our opinion be given to the investigation of a statistical relation between the abnormal propagation and the vertical profile of the refractive index.

Up to now it has been the opinion that this correlation is poor when individual observations are considered [Misme, 1957 and 1961; Maenhout, 1958].

2. Data and Definition of Variables

An examination was made of the field strength of the FM transmitter at Mierlo, near Eindhoven, as recorded continuously at The Hague (Netherlands) (fig. 1).

The frequency of the transmitter was 99.9 Mhz, antenna-height at Mierlo, h_1, 140 m, and at The

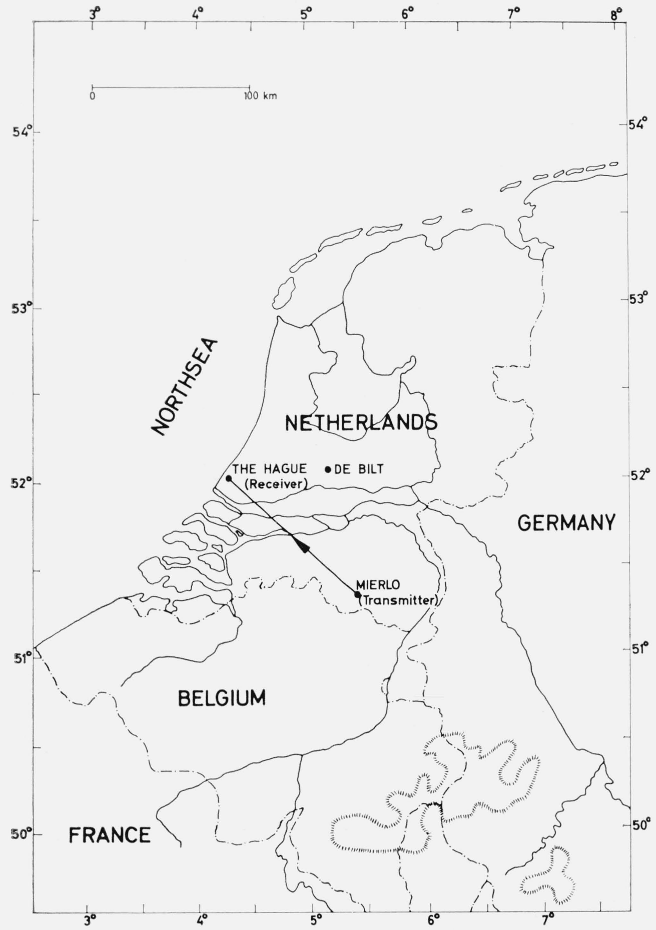

FIGURE 1. *Position of transmitter, receiver, and radiosonde station (De Bilt).*

Hague, h_2, 15 m; distance Mierlo-The Hague, 115 km. It can be shown from simple geometrical considerations that in case of rectalinear propagation the maximum distance d_m over which signals can be transmitted would be

$$d_m = 114(\sqrt{h_1} + \sqrt{h_2})$$

when h_1 and h_2 are expressed in kilometers. In case the atmospheric structure is that of the standard atmosphere and refraction is taken into consideration, the equation would change into

$$d_m = \sqrt{\frac{4}{3}} \times 114(\sqrt{h_1} + \sqrt{h_2}).$$

With the antenna-heights, as indicated above, this would mean:

$$d_m = 114 \times \sqrt{\frac{4}{3}} \times (\sqrt{0.140} + \sqrt{0.015})$$

$$\approx 65 \text{ km},$$

which means that for the Mierlo transmitter The Hague antenna is indeed considerably under the horizon.

The relation between the atmospheric structure as obtained from radiosonde observations at De Bilt and the field strength as observed in The Hague has been studied for the period July 1958–February 1960. As the times of the radiosonde observations are approximately 11.15 and 23.15 GMT, the field strength was averaged over periods of three hours centered at these times.

With regard to the meteorological parameters to be obtained from the radiosonde observation, the following points are of particular importance. The radiosonde station is not situated along the track between transmitter and receiver. Furthermore, the recordings of temperature and humidity as a function of height are discontinuous. Finally, the humidity observations are rather unreliable, which is in particular rather awkward, as the hydrolapse is of special importance. Also, as a result of the inertia of the thermometer and hygrometer, gradients of the refractive index computed on the basis of the usual data are too small, which means that the critical value of 0.157 m^{-1}, when present in the atmosphere, will often escape our attention.

However, in spite of these objections it is still worthwhile to obtain from the radiosonde observations an idea about the refractive index as a function of height.

Some authors have considered the difference of the refractive index at the surface and at a height of 1000 m [Bean and Meany, 1955], and others [Misme, 1960] paid particular attention to the refractive index near the ground. The use of these parameters probably yields some results when monthly or annual means with relation to scatter phenomena are discussed; their benefit is doubtful, however, when day-to-day variations in refractive propagation are investigated, as in such cases it is not always the situation at the surface or at 1000 m which is of crucial importance for the propagation of the waves.

For this reason the refractive index for each characteristic point of the radiosonde curve was computed by means of a graphical method [Air Defense Command Forecast Center, United States, 1952]. From this, the layer with the maximum gradient of refractive index and its magnitude were determined in the lowest 1500 m and in the lowest 3000 m. It was found that these gradients obtained from this lowest 1500 m were strongly related to the field strength; the gradients as obtained from the layer between 1500 m and 3000 m showed a less strong relation, thus indicating that the lower layers are the more important ones in this process of propagation.

3. Results of Statistical Tests

It is not unusual to determine in problems dealing with the relation between the gradients of refractive index and field strength, the correlation coefficient. Such a coefficient is an expression for the degree of linearity of the relation. However, in our case it is extremely doubtful whether there exists a linear relation at all, as in the vicinity of the critical value a small variation in the gradient induces large variations in the field strength. Furthermore, the variables show a very inhomogeneous distribution (there are, for example, several outliers), and in such cases the correlation coefficient is highly sensitive for some extreme values. For this reason the data were submitted to another statistical procedure. They were placed in a contingency table, which was subjected to a χ^2-test.

It should be stressed that as far as possible independent data should be considered, i.e., the pitfall resulting from persistence should be avoided [Van der Bijl, 1952]. If data originating from 12 hourly intervals are used, persistence may play an important role. In order to obtain an idea about the possible influence of persistence, autocorrelation coefficients of the maximum gradient of the refractive index of the first, second, etc. order, r_1, r_2, etc. (intervals 12, 24, 36, etc., hr) have been computed. For the month October 1958, which at first sight showed a great persistence, the following values for r_1 to r_5 have been found: 0.664, 0.352, 0.235, 0.131, and 0.051. The 10 percent level of significance with 60 observations is 0.165. As we want to avoid influences of persistence, it seems that r_4 and r_5 are sufficiently low. For a longer period, namely, July, August, September, October, and November 1958, $r_4=0.071$, which is again below the 10 percent level of significance of 0.077 belonging to a number of 285 observations.

In connection with the above, the following two points should be mentioned. The choice of the 10 percent significance level requires some explanation, since such a high level is usually considered as to provide a low degree of confidence with regard to the existence of a certain relationship. It should, however, be emphasized that in cases where the *absence* of a relation is under discussion, the 10 percent level gives a greater confidence than the lower levels.

It should furthermore be stated that the autocorrelation coefficients have been used to obtain a rough estimate of a possible persistence.

Returning now to the proposed contingency table, the following classes have been established: for the field strength >10 μv/m (reasonable reception), 5 to 9 μv/m (moderate reception), <5 μv/m (only noise); for the maximum gradient of the refractive index which varies between 0.030 m^{-1} and values higher than 0.157 m^{-1}, the classes were >0.100, 0.099–0.070, and <0.070. It would have been of interest if in the higher class a finer distinction could have been made; however, the number of data available for that purpose was too small [Cochran, 1952].

It was desirable, in view of the different structure of the atmosphere during the day and the night, in particular with respect to the large variation in the degree of turbulence, to consider night and day data separately.

It may be concluded from table 1, that at midnight the relation between the maximum gradient of the refractive index and the field strength is well established. This is even more clearly revealed when the probabilities of the occurrence of large field strength for various values of the gradient are computed, as indicated in the following table 2, which is, of course, only a modification of table 1.

a. *Night*

TABLE 1. *Relation at midnight between the maximum gradient of the refractive index between 0 and 1500 m and the field strength*

Field strength in μv/m	$\left(\frac{\delta N}{\delta h}\right)^{\max}_{0\text{–}1500\text{m}}$			
	<0.070	0.070–0.099	$\geqq 0.100$	Total
<5	115 (96)	18 (25)	4 (16)	137
5–9	45 (46)	12 (12)	9 (8)	66
$\geqq 10$	20 (38)	17 (10)	17 (6)	54
Total	180	47	30	[c] 257

$\chi^2=41.84$ $f=4$[a] $p<0.0001$[b]

[a] f=degrees of freedom.

[b] p=probability.

[c] Numbers between brackets represent expected frequencies, as usually computed from the marginal totals.

TABLE 2. *Probabilities* p *for field strength* $\geqq 10$ *μv/m at midnight*

	$\left(\frac{\delta N}{\delta h}\right)^{\max}_{0\text{–}1500\text{m}}$			
	<0.070	0.070–0.099	$\geqq 0.100$	All classes
p	0.11	0.36	0.57	0.21
σ	0.03	0.06	0.09	0.03

The increase in probability with increasing value of maximum gradient of the refractive index is undeniable, although it should be noted that the standard deviations in the columns 0.070–0.099 and $\geqq 0.100$ are rather high.

b. *Day*

TABLE 3. *Relation at midday of the maximum gradient of refractive index between 0 and 1500 m and field strength*

Field strength in μv/m	$\left(\frac{\delta N}{\delta h}\right)^{\max}_{0\text{–}1500\text{m}}$			
	<0.070	0.070–0.099	$\geqq 0.100$	Total
<5	155 (143)	17 (23)	10 (16)	182
5–9	39 (48)	13 (8)	9 (5)	61
$\geqq 10$	12 (15)	4 (3)	4 (2)	20
Total	206	34	23	263

χ^2 (as computed from classes with expected frequencies $\geqq 5$ only)=11.11, $f=4$, $p=0.025$

From table 3 it is seen that at midday the relation between the maximum value of the gradient of the refractive index and the field strength is also significant.

TABLE 4. *Probabilities* p *for field strength* $\geqq 10 \mu v/m$ *at midday*

	$\left(\frac{\delta N}{\delta h}\right)_{0-1500\text{m}}^{\max}$			
	<0.070	0.070–0.099	≧0.100	All classes
p	0.06	0.12	0.17	0.08
σ	0.02	0.06	0.08	0.02

Comparing now the results obtained for daytime and night observations, the following conclusion may be formulated:

The frequency of $\left(\frac{\delta N}{\delta h}\right)_{0-1500\text{m}}^{\max} \geqq 0.100$ at midnight does not differ substantially from that at noon (11.7% versus 8.7%). However, the occurrence of high field strengths is considerably greater during the night than during the day.

The relation between the maximum gradient of the refractive index and the field strength is during nighttime more pronounced than during daytime. This is particularly clear from the relative small variation of the probabilities of large field strength with various gradients of the refractive index (compare table 2 with table 4).

It is difficult to indicate the cause of the differences in the relationship. It may be suggested that in order to obtain abnormal propagation apart from a large gradient in the refractive index, also a stable atmosphere with low turbulence in the lower levels will be necessary. One might also expect that differences in ground-based ducts partly account for the differences between the relationship during night and day.

If the above suggestions are correct, then it will be likely that we find analogous indications when comparing data of winter and summer.

In table 5 the probabilities p are given for high field strengths during summer and winter, and for night and day.

TABLE 5.—*Probabilities* p *for high field strength* ($\geqq 10$ $\mu v/m$) *during summer and winter, for night and day, separately*[a]

		$\left(\frac{\delta N}{\delta h}\right)_{0-1500\text{m}}^{\max}$				
		<0.070	0.070 0.099	≥ 0.100	All classes	probability of $\left(\frac{\delta N}{\delta h}\right)_{0-1500\text{m}}^{\max} \geq 0.100$
Winter (September to February)	Midnight	0.12 (123)	0.35 (20)	0.67 (12)	0.19 (155)	0.08
	Midday	0.09 (127)	0.18 (17)	0.33 (12)	0.12 (156)	0.08
Winter	Total	0.10	0.27	0.50	0.15	0.08
Summer (March to August)	Midnight	0.09 (57)	0.37 (27)	0.50 (18)	0.24 (102)	0.18
	Midday	0.01 (79)	0.06 (17)	0.0 (11)	0.02 (107)	0.10
Summer	Total	0.04	0.25	0.31	0.13	0.13

[a] Figures between brackets represent absolute numbers, from which the probabilities have been computed.

It appears from this table that during summer daytime no relation between the maximum gradient of the refractive index and the field strength seems to be present. Some caution should, however, be exercised, since the number of observations on which this conclusion is based is too small to guarantee more than a suggestive evidence.

4. Summary

1. The relation between atmospheric structure and the propagation of UHF radio waves from a source under the horizon was investigated. The atmospheric parameter was the maximum value of the gradient of the refractive index in the layer between surface and 1500 m.

2. The relation between these variables was found to be rather strong at midnight but was less pronounced at noon.

This seems to indicate that apart from a large gradient of the refractive index, also a stable atmosphere in the lower levels is conducive to abnormal propagation. This idea is corroborated by the fact that in the noon observations made during summer months, no relation whatsoever exists between the two variables.

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