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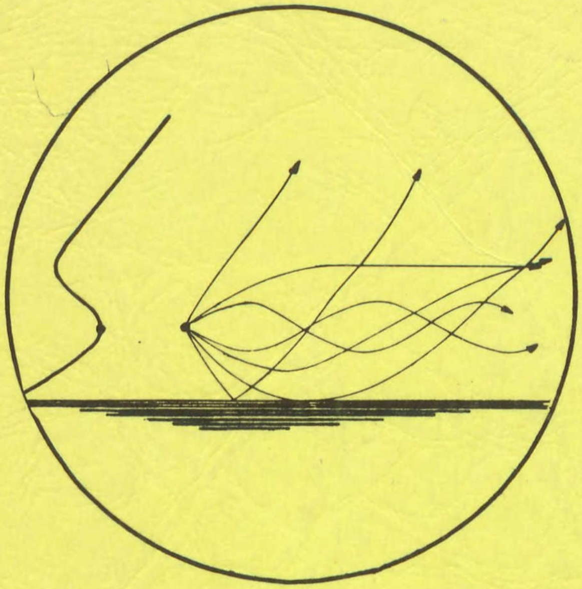

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SURVEY ON RADIO PROPAGATION IN TROPOSPHERIC DUCTS

by

Donald R. Hay and C.L. Ting

Department of Physics

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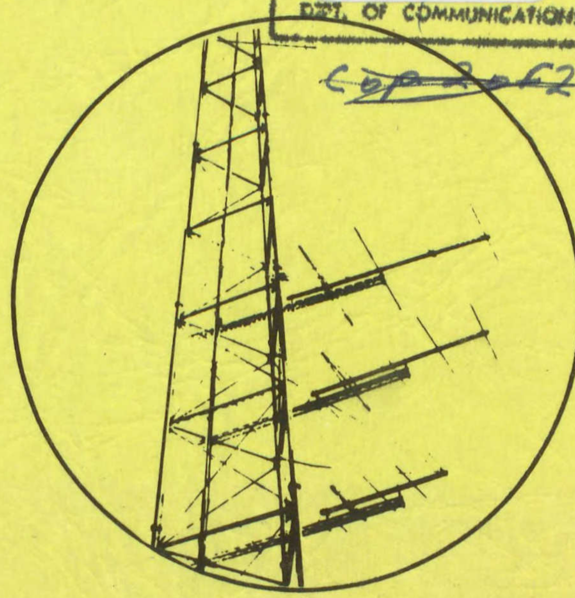

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SURVEY ON RADIO PROPAGATION IN TROPOSPHERIC DUCTS

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ABSTRACT

Microwave ducting in the lower troposphere is governed by local perturbations of temperature and humidity within their mean vertical profiles. Surface ducting is confined to the lowest 100 m., while elevated ducting may occur commonly at heights up to several hundred meters. Generally, surface ducting results in radio signal enhancements up to 50 db above the free-space level. In contrast, elevated ducting may lead either to signal enhancement of several db or to signal degradation (fading or "radio holes") as much as 30 db below the normal level. Surface ducting is associated with evaporation from water surfaces or saturated land, and with radiational cooling of the surface, - especially at sub-freezing temperatures above snow. Elevated ducting is a more migratory phenomenon, usually related to subsidence of air masses above an anticyclonic area, advection of warm and dry air above a cooler and more moist surface layer, and occasionally with the intrusion of weather fronts. The analysis of ducting is reviewed for the ray approach and for the full-wave theory, and the refractivity profile requirements for ducting are noted. Current theories predict ducting signals in the diffraction region with good success, but improvement is desirable for signals in the interference region. Microwave frequencies supported by ducts and the modification of the interference radiation pattern by ducts both are predicted by these theories, when the refractivity profile is specified. The present trends in ducting research are towards extension of the mode theory in the wave analysis of ducting, the prediction of ducting fields over water in the interference region from routine surface air and water

observations, the development of sensing devices to provide detailed refractivity profiles in the vertical and horizontal, the inclusion of horizontal inhomogeneity of refractive index in the theory of ducting, and the effects of air turbulence and terrain roughness in this theory. A short commentary is included on ducting research in the Canadian environment, and on the need for extension of this work.

LIST OF SYMBOLS

a	radius of the earth	(Eq. 2.4)
a_e	effective radius of the earth	(Eq. 2.5)
A_1, A_2	ray focusing factors	(Eq. 3.8)
d	duct height or duct width	(Eq. 2.9)
D	transmitter-receiver distance	(Eq. 4.3)
e	partial pressure of water vapour	(Eq. 2.1)
E	electric field intensity	(Eq. 3.8)
E_o	free-space field intensity	(Eq. 3.8)
E_1, E_2	radio field components defined in Eq. 4.10	
f_{min}	minimum signal frequency supported by duct	(Eq. 3.12)
g_α	wave solutions of Eq. 4.4	
G_o	obstacle gain	(Eq. 4.10)
h	roughness scale height	(Eq. 4.9)
h_o	scale height	(Eq. 4.6)
h_2	receiver height	(Eq. 3.10)
k	wave number	(Eq. 3.1)
K	lapse-rate of m at remote height	(Eq. 4.5)
m	modified refractive index	(Eq. 2.4)
n	refractive index of the air	(Eq. 2.1)
n_o	surface refractive index	(Eq. 2.5)
p	total air pressure	(Eq. 2.1)
q	specific humidity	(Eq. 2.6)
r	length of ray path	(Eq. 3.10)
$\vec{r}$	radial distance vector (geocentric)	(Eq. 4.1)
R	Fresnel reflection coefficient	(Eq. 3.8)

LIST OF SYMBOLS (cont'd)

R'	Rayleigh roughness parameter	(Eq. 4.9)
s	distance along ray path	(Eq. 3.2)
T	absolute air temperature	(Eq. 2.1)
U, V	fields of Hertzian dipole	(Eq. 4.1)
z	height above the earth's surface	(Eq. 2.4)
z_o	roughness length of the surface	(Eq. 2.10)
z_1	height of measurement of atmospheric parameters	(Eq. 2.12)
Z_s	free-space wave impedance	(Eq. 4.1)
α	damping coefficient	(Eq. 4.10)
$\alpha(h_1)$	transmitter radiation angle	(Eq. 3.10)
β	period parameter	(Eq. 4.10)
Γ	evaporation coefficient of water surface	(Eq. 2.8)
Γ_1	profile coefficient	(Eq. 2.11)
$\Gamma(t)$	incomplete and complete gamma functions	(Eq. 4.6)
λ	wavelength	(Eq. 3.9)
θ	potential temperature	(Eq. 2.6)
$\phi(R_i)$	stability function (depending on Richardson number)	(Eq. 2.10)
ϕ_1, ϕ_2	phases of direct and reflected waves	(Eq. 3.8)
ψ	scalar wave function	(Eq. 3.1)
ψ'	grazing angle for rays incident on surface	(Eq. 4.9)

1. INTRODUCTION

At the request of the Communications Research Centre (Ottawa), a study of radio ducting in the troposphere has been undertaken by the Centre for Radio Science in January 1974. This project is divided into two phases. One phase requires the preparation of a literature survey on tropospheric ducting; the present report is directed towards this end. The second phase will define a project and the associated equipment design for an experimental study of ducted propagation. The latter has begun in parallel with the literature survey, while making use of the results of this survey. Reports on this second phase will be given elsewhere.

This report provides a selective review on tropospheric ducting. All of the cited references are found in scientific journals and open publications. Information on operating experience in Canadian communications links and air traffic control radars has been made available to the present authors, but this has been used only in preparing the commentary at the end of this report. Of importance here is the assessment of ducting research as it applies to the Canadian environment. Topics of special relevance are the prevalence and severity of ducted propagation, the dependence on operating frequency, path length and nature of the equipment, on the type of terrain and topography, and on the climate and meteorological conditions.

The reader will be aware of certain milestones in ducting research. The phenomenon of ducting jumped into prominence during the 1940's, as a source of anomalous radar signal propagation, especially on overwater paths. Urgent studies at that time were able to define the parameters of ducting, and indeed to lay a useful theoretical basis for later work. Comprehensive volumes provide detailed accounts of that earlier work (see, for example, Kerr 1951; Booker and Walkinshaw 1946)*. Subsequent progress has depended upon four improvements of attack: the mathematical formulation of ducting, the advent of electronic computers to carry out the tedious calculations required, the development of special sensors to observe the small-scale meteorology of ducting, and the development of adequate theories of thermal and vapour diffusion in the turbulent region of the lower troposphere. The extent of progress during 30 years is indicated in the proceedings of a recent Advanced Study Institute (Zancla 1973).

The present survey is divided into four sections. The first refers to the refractive index profile and its dependence upon local meteorology. The second reviews the ray analysis of microwave transmissions through ducting refractivity profiles. The more elaborate analysis of wave theory is noted in the third section, and the fourth section describes ducting experiments in the Canadian environment.

*References in the body of this report are listed in Section 7. Additional bibliography on microwave ducting is found in Section 8.

This is followed by a commentary on the present needs for ducting research in Canada.

The writers are grateful to Dr. A.W. Adey of the Communications Research Centre for his assistance in the assembly of the bibliography, and in the procurement of special documents.

2. DUCTING METEOROLOGY AND REFRACTIVE INDEX

An excellent survey on air refractivity in the troposphere at radio frequencies is found in Bean and Dutton (1966). Those aspects that are important to radio ducting in the lower troposphere are noted briefly in this Section. More recent contributions also will be included.

2.1 Tropospheric Refractivity

The relationship between the refractive index and the physical parameters of the air is well-known. For a dielectric medium of negligible conductivity and unity permeability, the refractive index for a plane electromagnetic wave is governed by the polarizability of the molecules. The air in the troposphere generally has these characteristics, and its polarizability contains a permanent component associated with all of the constituent molecules and an induced component for the water molecules (Debye 1929, Ch. 1 and 2).

Tropospheric air may be treated as an ideal gas in the absence of precipitation. Then, the dependence of refractive index (n) upon these molecular polarizabilities is expressed by the following equation:

$$n = 1 + \frac{C}{T}\,(\text{total air pressure, } p) + \frac{D}{T^2}\,(\text{partial water vapour pressure, } e) \quad \ldots.(2.1)$$

where T is absolute temperature, and C and D are constants that depend upon the molecular composition. The latter have been examined through numerous laboratory measurements, and the following form of Eq. (1) has been derived (Smith and Weintraub 1953):

$$n = 1 + \frac{77.6 \times 10^{-6}}{T} \left[p(mb) + \frac{4810}{T} e(mb) \right] \qquad \ldots.(2.2)$$

The coefficients are somewhat different from those used in earlier refractivity equations, but this equation is widely accepted at the present time, for tropospheric air of standard composition.

Eq. (2) is accurate within 10^{-6} in refractive index for the range of T, p and e normally found in the troposphere (Bean 1962). Further, it applies throughout the radio spectrum from DC to 30 GHz. Significant departures occur at frequencies above 30 GHz because of resonance absorption associated with the O_2 and H_2O molecules. These resonances are centred at 20, 60, 120, 177, 323, ...GHz. The relationship between radio signal absorption and change of refractive index at each resonance is given by Stratton (1941, Sect. 5.14) and Kerr (1951, Sect. 8.1). For the resonance at 22 GHz, the measured absorption (due to H_2O) is of the order 0.2 db km^{-1}; the resonance theory indicates that the associated change in refractive index is less than 10^{-6} (Bean and Abbott 1957; Liebe 1969; Fowler and LaGrone 1969; Thompson, Vogler, Janes and Wood 1972).

Radio attenuation becomes appreciable at frequencies above 30 GHz and in the presence of precipitation (see, for example, Hay 1969). The nature of these resonances and of their effects upon the neighboring frequencies is the subject of current research as noted in the above references. Precipitation attenuation normally is not important in ducting phenomena. The mixing of air in rain or snow fall will tend to destroy the stratificiation of refractivity that is required in ducting. Further, a superrefractive m-profile usually becomes sub-refractive (non-ducting) when e is reduced by a change from the vapour to liquid phase in fog precipitation (Bean and Dutton 1966). Microwave attenuation by fogs rarely exceeds 1 db km^{-1}.

2.2. Refractivity Perturbations

The relationship between small changes in air refractivity and the parameters of the air will be considered next. For the depth of the troposphere, mean profiles of refractive index may be derived from conventional radiosonde information on temperature and humidity through the application of Eq. (2). These are illustrated in Fig. 1 for four types of air mass above Maniwaki, Ontario (Hay 1958). In each case, the total refractivity decreases monotonically with height from a maximum value near the surface. As may be expected, the contribution from water vapour is greater in the maritime Tropical air (normally found frequently in the summer) than in the continental Arctic air (commonly present in winter). Short-term variations occur about each mean profile, especially at heights below several

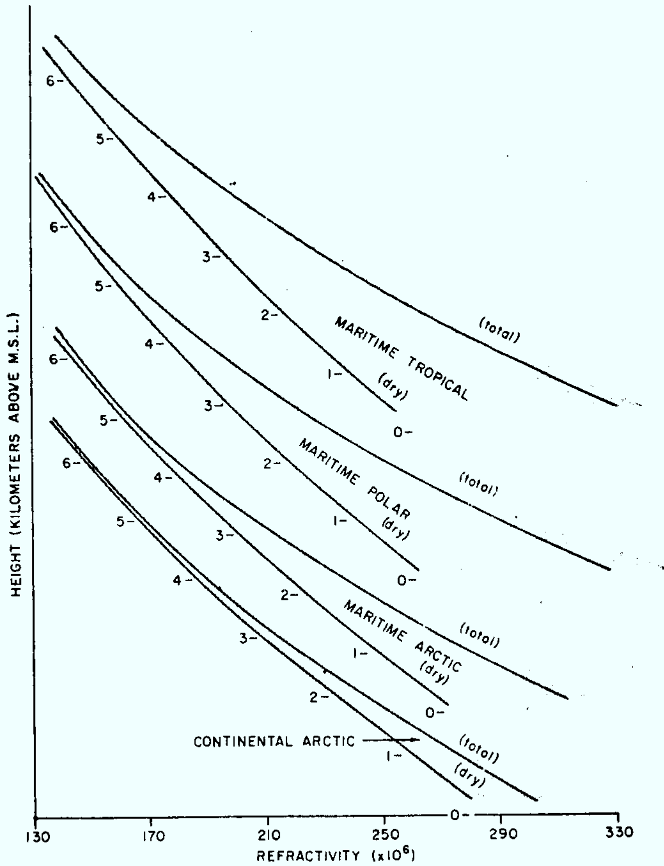

Fig. 1: Total and dry refractivities for air masses over central Canada. (Hay 1958)
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kilometers. These are associated with local perturbations of temperature ($\Delta T \sim 1C$), humidity ($\Delta e \sim 1$ mb), and pressure ($\Delta p \sim 0.1$ mb), for reasons that will be considered later. The effects of these perturbations upon air refractivity are seen through the differential form of Eq. (2):

$$\Delta n = a \cdot \Delta T + b \cdot \Delta e + c \cdot \Delta p \qquad .....(2.3)$$

$$\text{where } a = -\frac{77.6 \times 10^{-6}}{T^2}\left(p + \frac{9620\ e}{T}\right)$$

$$\simeq -1.2 \times 10^{-6} \text{ near the surface,}$$

$$b = 0.373\ T^{-2}$$

$$\simeq 4.5 \times 10^{-6} \text{ near the surface,}$$

$$c = 77.6 \times 10^{-6}\ T^{-1}$$

$$\simeq 0.3 \times 10^{-6} \text{ near the surface.}$$

Clearly, the perturbations in vapour pressure and temperature far outweigh the pressure perturbations in introducing refractivity fluctuations. The meteorological processes that accompany temperature and humidity fluctuations will be reviewed below.

2.3 Profiles of Modified Refractive Index

The concept of modified refractive index or the "flat-earth approximation" continues to serve a useful purpose in the analysis of radio ducting. It will be noted briefly here, before discussion is continued on atmospheric refractivity profiles.

In the analysis of wave progression through the atmosphere, it is convenient to refer heights to the spherical surface of the earth. A simplification in space coordinates is available in this case (Kerr 1951, Sect. 2.4). When Maxwell's wave equations for free space are written in a coordinate system that is appropriate for the spherical tropospheric shell, they are reduceable to the more familiar rectangular coordinate system if the true refractive index of the air (n) is replaced by the modified refractive index (m) according to:

$$m = n(1 + z/a) \qquad .....(2.4)$$

where z is height above the earth's surface, and a is the radius of curvature of the earth's surface. With this transformation, the earth's surface may be treated as a horizontal plane (z=0), for radio transmission over distances of many 10's of kilometers.

The vertical profile of true refractive index is transformed into m-profiles of special significance. For example, a "reference refractive index profile" (curve 1, in Fig. 2a) becomes a homogeneous atmosphere (curve 1, in Fig. 2b) in which horizontal waves move parallel to the earth's surface. In this case, Eq. (4) becomes:

$$m = n_o(1 + z/a_e) \qquad .....(2.5)$$

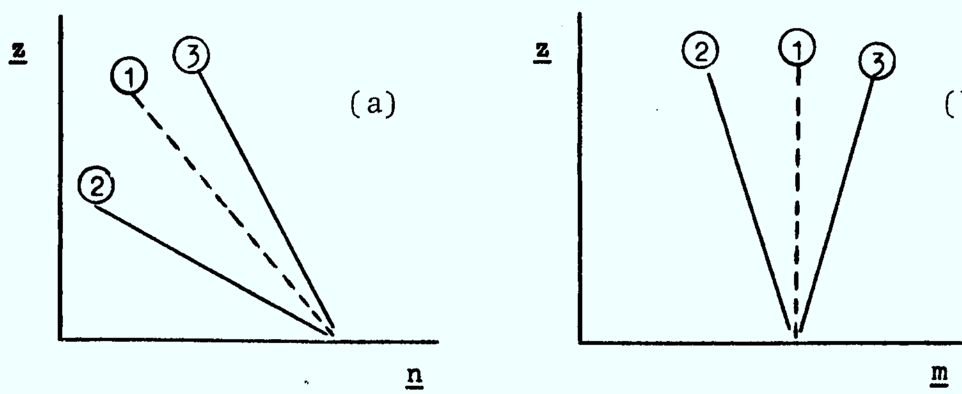


Fig. 2: Corresponding vertical profiles of true refractive index (n) and modified refractive index (m).

where n_o is the refractive index of the air at the surface, and a_e is an "effective earth's radius" (nominally 4a/3). As will be noted later, profiles (2) and (3) lead to wave-path curvatures in opposite sense, and in combination they are associated with radio ducting.

Several basic forms of m-profile are illustrated in Fig. 3. These are: (1) substandard surface layer, (2) profile for standard refraction, (3) superstandard surface layer, (4) superstandard surface layer with surface duct, (5) elevated superstandard layer with surface duct, (6) elevated superstandard layer with elevated duct, and (7) surface and elevated superstandard layers with both surface and elevated ducts (Kerr 1951, Sect. 1.4). For later reference, we note that the ducts extend through the height intervals indicated by broken lines.

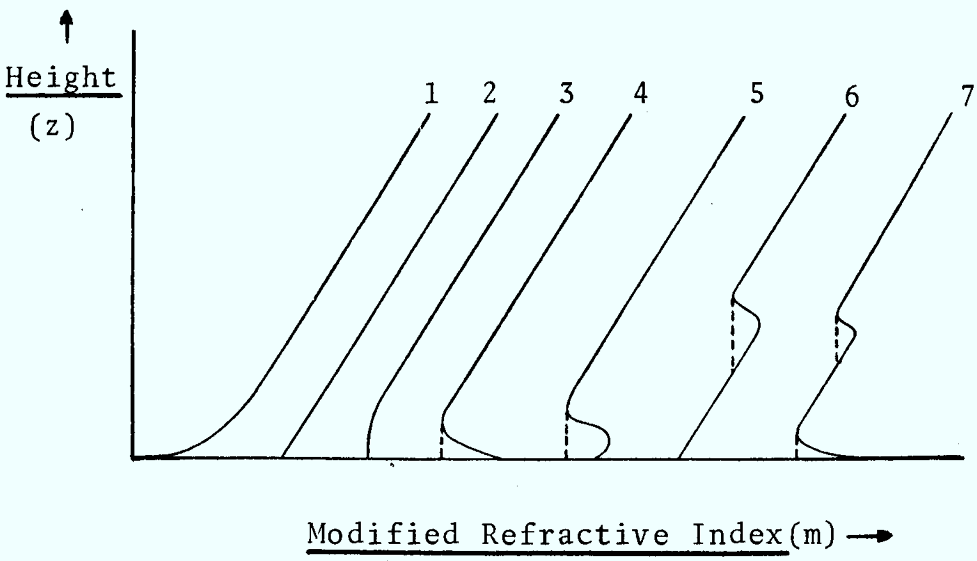


Fig. 3: The basic forms of m-profile of importance to radio ducting.

2.4 Surface and Elevated Ducts

Three layers in the lower troposphere are significant in radio ducting (Kerr 1951, Ch. 3). These are the surface layer extending from the surface upwards to several tens of meters, a central layer several hundred meters deep above this, and the upper layer that is much deeper than the other two. The temperature lapse rate is stable in the latter, adiabatic in the central layer, and variable in the surface layer. Turbulence generally is well developed in the lower two layers, and hence the adiabatic lapse rate is a common characteristic of both. Departures from this temperature profile in the lowest layer are due to its proximity to the surface.

Microwave ducting occurs most commonly within the lower two layers. In order to assess the role of temperature and humidity in ducting, it should be noted that potential temperature (θ) and specific humidity (q) are conservative quantities in unsaturated air. Then the vertical m-gradient is related to the vertical gradients of the latter by (Kerr 1951, Sect. 3.7)

$$\frac{dm}{dz} = -c_1 \frac{d\theta}{dz} + c_2 \frac{dq}{dz} + c_3 \qquad \text{....(2.6)}$$

where c_1, c_2 and c_3 are specified functions of T, p and e. In well-mixed (turbulent) air, $\frac{d\theta}{dz}$ and $\frac{dq}{dz}$ vanish and

$$\frac{dm}{dz} = c_3 = 1.3 \times 10^{-7}\ m^{-1} \qquad \text{.....(2.7)}$$

The linear segments of the m-profiles in Fig. 3 with positive slope are described by Eq. (2.7); these apply to layers of well-mixed air.

Those segments of the m-profiles in Fig. 3 where $\frac{dm}{dz} \leq 0$ are of present interest. A number of meteorological situations that create these perturbations have been suggested from experiments in the U.S.A. These are:

(a) Surface ducts -

(i) nighttime radiational cooling of the ground.

(ii) offshore flow of warm air during daytime (strong insolation)

(In each of these cases, the intensity of the perturbation will be governed by the relative contributions of θ and q in Eq. (6), since their gradients introduce opposing tendencies in $\frac{dm}{dz}$)

(iii) frontal passage, introducing suddenly a volume of cooler and drier air above a warm surface.

(b) Elevated ducts -

(i) subsiding dry air above an area of high pressure that is subject to divergence at the top of the mixing layer.

(The thermal stability of the subsiding air is intensified and a localized temperature inversion appears aloft. Semi-permanent systems of this type occur commonly off the coast of California).

(ii) frontal inversion, at the quasi-horizontal boundary between a drier air mass above and well-mixed moist air below.

(iii) elevation of a nighttime radiational cooling layer, through strong surface winds (turbulent mixing of the surface air).

2.5 The Evaporation Duct

This is the most common and widely studied form of radio duct. Evaporation from a water surface (or saturated land surface) is enhanced by the turbulent diffusion in a wind. The depth of the surface duct may grow to some 100m. for wind trajectories of order 40 miles.

Analysis of the evaporation duct has developed gradually over a period of 30 years. In an early approach (Kerr 1951, Sect. 3.15) the theory of vapour diffusion yielded the gradient of specific humidity:

$$\frac{\partial q}{\partial z} = - z \quad \Gamma \, \Delta q \qquad \text{....(2.8)}$$

where Γ is the evaporation coefficient of the surface, and Δq is the humidity deficit between the surface and the well-mixed layer above. Combining Eq. (8) and (6), noting that $\frac{d\theta}{dz}$ vanishes in well-mixed air, and defining the duct height (d) by the level at which $\frac{dm}{dz}$ vanishes, leads to:

$$\frac{d}{\Delta m} \simeq 0.6 \times 10^{-6} \text{ meter} \qquad \text{....(2.9)}$$

where Δm is the m-deficit between the surface air and that in the well-mixed region above it. Experimental measurements on overwater paths indicate that Eq. (9) gives the upper limit for d in various atmospheric stabilities.

A recent treatment of the same type of duct (Jeske 1973) replaces Eq. (8) by a more general form. This is:

$$\frac{\partial q}{\partial z} = - \frac{\Delta q}{z + z_o} \phi(Ri) \left[\int_o^z \frac{\phi(Ri)}{z + z_o} dz \right]^{-1} \qquad \text{....(2.10)}$$

where $\phi(Ri)$ is a specified stability function (of the Richardson number or the Monin-Obukhov length) and z_o is the roughness length of the surface. An equation of similar form applies to $\frac{d\theta}{dz}$. Following the procedure noted above, the corresponding form of Eq. (9) becomes:

$$\frac{d}{\Delta m} \simeq \frac{\Gamma_1 \times 10^{-6}}{0.125} \text{ meter} \qquad \text{...(2.11)}$$

Here, Γ_1 is a profile coefficient that has been evaluated experimentally for a wide range of $\phi(Ri)$; it lies between 0.05 and 0.18. Thus, Eq. (9) becomes a special case of Eq. (11) for near-neutral stability of the air.

A model of the m-profile through an evaporation duct has been developed by Früchtenicht (1973). This requires measurements of temperature and vapour pressure at the sea surface and at height z_1, both within the constant-flux layer. The terms in Eq. (6) are evaluated with this information, and the equation is integrated in the vertical to give:

$$m(z) = (\text{constant})\left[(z - z_1) - (d + z_o) \ln \frac{z + z_o}{z + z_1}\right] + m(z_1) \quad \ldots.(2.12)$$

This "log-linear" profile reduces to a linear m-profile when the duct vanishes.

2.6 Prediction of Surface Ducting and Persistent Elevated Ducting

Considerable effort is being directed towards the prediction of evaporation ducts over the sea at the present time. To this end, the processes of vapour transfer above the sea surface are being studied over open waters (see, for example, Laevastu 1973; Bean and Emmanuel 1973; Hamilton and Laevastu 1973; and Hasse 1973), and in special wind-tunnel laboratories (Coantic 1973; Bolgiano and Warhaft 1973).

In Norway, L-band radars operating over north-western Europe have recorded intervals of elevated ducting over a 3-year period. (Gjessing and Moene 1967). These resulted in signal increases at least 40 db above the normal level. Comparison with weather records showed a correlation better than 80 percent between signal ducting and a refractivity depression greater than 15×10^{-6} at the 850 mb level. As noted in Sect. 2.4, these are attributed to a warm, dry air mass aloft above cooler and more moist air at the surface, associated with northward advection from the Mediterranean area to N.W. Europe, or with the subsidence above an anticyclonic area. Daily synoptic charts currently are prepared for 36 - hour forecasts of ducting conditions, with successes comparable to those found in routine weather forecasts.

Predictions of surface ducting overwater on the regional scale follow the Norwegian theory for numerical computation of evaporation duct thickness (Laevastu 1973, Hamilton and Laevastu 1973). This assumes convective turbulent evaporation, and takes into account the trajectory of the surface air. Routine weather observations provide the required information on sea-surface temperature, air humidity, and mean wind vector. It is found that the coastal influence extends offshore some 10-50 nautical miles. Computerized drawings of radar coverage in ducting conditions are presented from the ducting profiles. Further work is desirable on the relationship between ducting characteristics and the parent air masses.

2.7 Measurement of m-profiles

Details of the m-profile along a radio transmission path are important to the analysis and the theory of ducting. Evidence of horizontal inhomogeneity (Miller, Halbert, Doherty and Swanson 1947; Jeske 1973; Bean and Dutton 1966) suggests the need for profile observations frequently and at several points along a transmission path. Appropriate instrumentation for this purpose is discussed in Hall(1971), Hay(1971), Jeske(1973) and Bolgiano and Warhaft(1973).

3. RAY ANALYSIS OF DUCTING (GEOMETRICAL OPTICS)

Some insight into the ducting of radio waves by the atmosphere is derived through ray analysis of selected m-profiles. The technique has important limitations. Some of these limitations have been reduced by extending ray analysis towards wave analysis. These points will be reviewed briefly in this Section.

3.1 The Basis of Ray Analysis

The analysis of waves progressing from a source begins with Maxwell's equations (Kerr 1951, Section 2.3 - 2.5). The appropriate solutions must depend, in turn, upon approximate solutions to the scalar wave equation:

$$\nabla^2\psi + k^2n^2\psi = 0 \qquad ....(3.1)$$

where k is the wave number, n is the refractive index of the medium, and ψ has the form

$$\psi = Q \exp(-iks) \qquad ....(3.2)$$

as governed by the equation of the eikonal:

$$(\nabla s)^2 = n^2 \qquad ....(3.3)$$

Eq. (3) leads to four conditions on the progression of the wave-front (i.e. on the ray path):

(a) curvature of the ray = (radius of curvature of the ray)$^{-1}$

$$\simeq |\nabla n| \qquad ....(3.4)$$

for quasi-horizontal rays,

(b) Fermat's principle

(c) Snell's law

(d) the rays are plane curves when ∇n is in a fixed direction.

The ray analysis of wave progression between a transmitter and receiver requires consideration of the full field of rays. A single ray has little significance. For such a field, the ray treatment is valid when:

(a) the refractive index of the medium does not change appreciably in a distance of one wavelength, and

(b) the fractional change in spacing between neighboring rays is small relative to unity, over a distance of one wavelength.

These conditions usually are met for microwaves and millimeter waves in the atmosphere outside of focal points and caustics in the ray pattern.

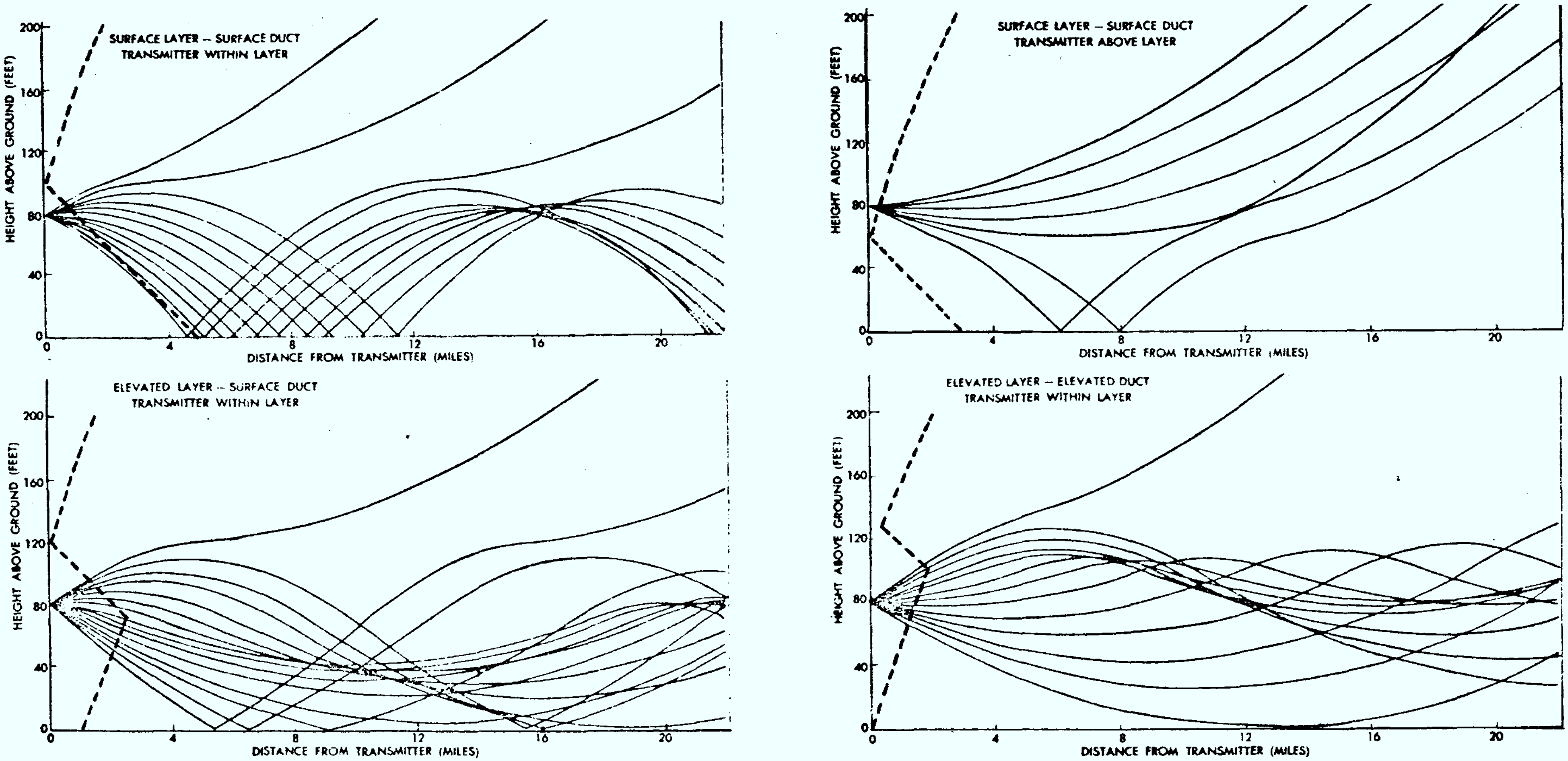
3.2 Conditions for Atmospheric Ducting

Ray analysis of microwave transmissions in atmospheric ducting has been used extensively since the 1940's. A summary report on earlier work in the UK and U.S.A. was prepared by the NDRC (1946). Doherty (1953) has pointed out that some applications were not productive because the limitations of Sect. 3.1 were not observed. Specifically, wavelength dependence in ducting transmissions is not evident in ray analysis, and some meteorological effects (e.g. attenuation by precipitation) are not taken into account. However, the advantagesof ray analysis clearly are evident in the interference region, where physical optics (see Sect. 4) requires the summation of a large number of modes. More exact and laborious treatment may be applied to focal regions and caustics in the ray analysis for improved assessment of the field strength.

Fig. 4 shows five ray diagrams for ducting m-profiles (Doherty 1953). These represent surface ducting and elevated ducting of microwave signals, for various positions of the transmitter antenna relative to the ducting layer. The corresponding m-profiles are given by broken lines on the left of each diagram; these may be compared with the basic profiles of Fig. 3. Wide separtion of adjacent rays suggests regions of relatively weak field intensity. Convergence of adjacent rays along caustics suggests the possibility of relatively strong field intensity; in these cases, the caustics should be examined further through the Airy integral, and full-wave solutions of physical optics should be applied to regions of apparent reflection.

The conditions for a ducting m-profile may be seen through inspection of Fig. 4. Within the interference region, an atmospheric layer becomes a duct by confining a bundle of progressing rays to its depth. For a surface duct, the rays progress through repeated reflection from the earth's surface, and the duct thickness (d) is specified by

$$\frac{dm}{dz} \begin{matrix} < \\ = \\ > \end{matrix} 0 \qquad \text{for } z \begin{matrix} < \\ = \\ > \end{matrix} d \qquad \ldots(3.5)$$



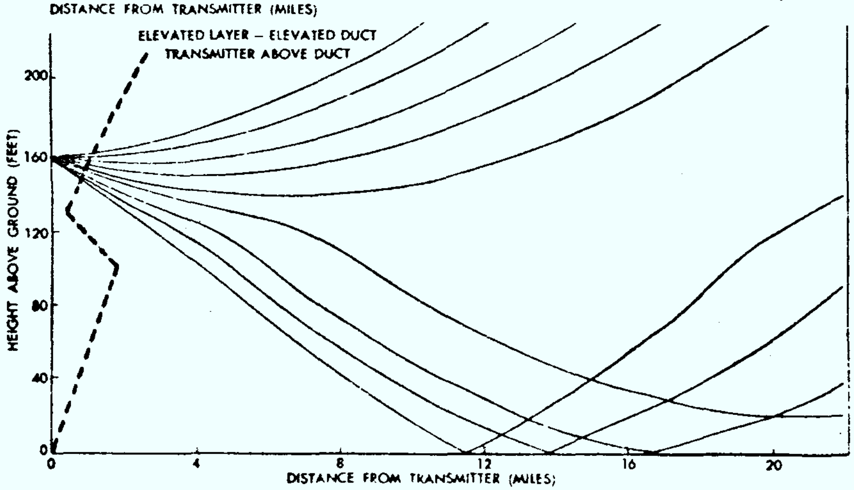


Fig. 4: Examples of ray diagrams for various ducting configurations. (m-profile indicated on the left of each diagram. Transmitter at 80 ft. or 160 ft.) [Doherty 1953].

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An <u>elevated duct</u> may confine the progressing rays about a height for which

$$\frac{dm}{dz} = 0 \qquad \text{....(3.6)}$$

provided that

$$\frac{d^2m}{dz^2} > 0 \qquad \text{....(3.7)}$$

around that height. Wong (1958) describes ray-tracing in more detail, with numerous examples.

3.3. Extension Towards Wave Analysis

Earlier work on field strengths in the interference region combined the techniques of wave theory and ray analysis (Kerr 1951, Sect. 2.11). The field at the receiver was the resultant of two waves from the transmitter, one following the direct ray path and the other following the path of a surface-reflected ray. Provision was made for divergence of the reflected ray because of the spherical surface of the earth. However, the applications were confined to atmospheres with linear m-profiles.

Recently, Früchtenicht (1973) has formulated this approach to deal with ducting m-profiles. The electric field strength (E) is given by

$$|E|^2 = E_o^2[A_1^2 + |R|^2 A_2^2 + 2|R|A_1A_2 \cos(\phi_2-\phi_1)] \qquad \text{....(3.8)}$$

where E_o is the free-space field, R is the Fresnel reflection coefficient of the earth's surface, ϕ_1 and ϕ_2 are the phases of the direct and reflected waves, and A_1 and A_2 are focusing factors for the direct and reflected ray bundles (relative to the free-space field). The values of ϕ_1, ϕ_2, A_1 and A_2 are governed by Eq. (4) for a horizontally-stratified atmosphere, leading to

$$\phi = \frac{2\pi}{\lambda} \int_s m\,ds \qquad \text{....(3.9)}$$

for integration along the ray path s, and

$$A^2 = \left| r \frac{d\alpha(h_1)}{dh_2} \right| \qquad \text{....(3.10)}$$

where r is the physical length of the ray path, $d\alpha(h_1)$ and dh_2 are the differentials of the transmitter radiation angle and of the receiver height, respectively.

3.4 Effects of Duct Thickness on Signal Transmission

The ducting theory proposed by Früchtenicht (1973) has been applied to surface ducts with log-linear m-profiles. Fig. 5 illustrates sample predictions of the height-gain at the receiver. The normal interference lobe pattern as found in the absence of ducting is represented by the solid-line profiles. Surface ducting modifies this pattern in three ways: it changes the ratio of E_{max}/E_{min}, it introduces height-damping into this ratio, and it alters the height of the lowest maxima/minima. The latter tends to decrease with increasing duct thickness. If the receiver is at fixed position, it will observe the changing lobe structure as the duct thickness changes; the number of lobes will increase as the transmitter-receiver distance increases.

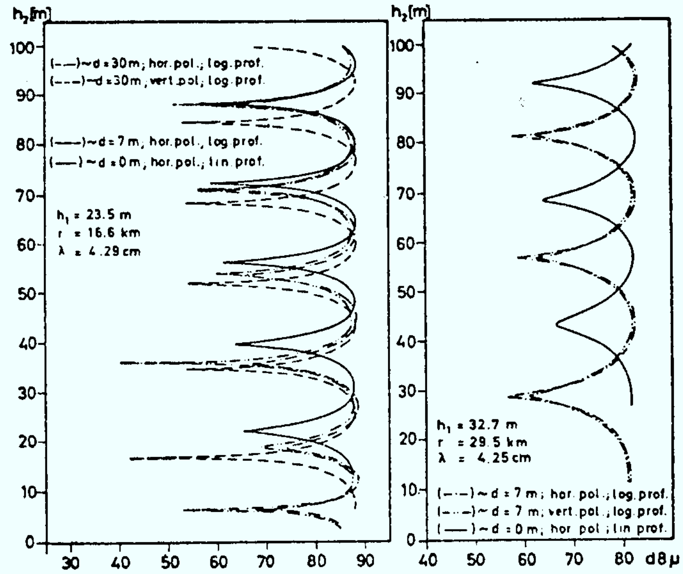

Fig. 5: Receiving field-strength as a function of the receiver height.

(Früchtenicht 1973)

(Reproduced with permission of the publisher)

This lobe pattern is absent within the diffraction region. However, the received signal amplitude increases with increasing duct thickness. This has been confirmed through extensive experiments over the North Sea and Atlantic Ocean through evaporation ducts (Jeske 1973), at least for wavelengths up to 53 cm. For longer wavelengths, surface ducting effects weaken until they disappear at λ = 1.8 m. The theortical prediction of field strength is sensitive to small changes in the assumed m-profile.

The maximum signal wavelength that is supported by a surface duct may be estimated from the duct parameters (Kerr 1951, Sect. 1.5). Through considerations similar to those used in waveguide theory, but assuming a linear m-profile through the duct and noting a $\pi/2$ change in phase upon reflection at the top of the duct, the maximum guided wavelength is given by

$$\lambda_{max} = \frac{8\sqrt{2}}{3} \int_0^d [m(z) - m(d)]^{1/2} dz \quad .....(3.11)$$

This may be re-written (Bean and Dutton 1966, Sect. 4) for minimum frequency:

$$f_{min} \text{ (Hz)} = \frac{1.2 \times 10^5}{d^{3/2} \left[- \frac{dn}{dz} - \frac{1}{a}\right]^{1/2}} \quad .....(3.12)$$

where distances and heights are in km. In particular,

$$\frac{dn}{dz} \leq - 157 \times 10^{-6} \text{ km}^{-1} \quad .....(3.13)$$

defines the trapping limit according to the condition of Eq. (6) Bean, Cahoon, Samson and Thayer (1966) have analyzed radiosonde profiles in view of Eq. (12) and (13), to give global contours of f_{min} for surface ducting, for various months of the year.

3.5 Horizontal Inhomogeneity and Frontal Effects

The theory of ducted transmission of radio waves conventionally assumes that the refractivity of the air at a specified height is the same along the radio path (horizontally stratified). While this assumption may be reasonable for time averages over several days or weeks, significant inhomogeneities along the horizontal appear on a shorter time-scale. One example is the intrusion of a weather front along the radio path. Bean and Dutton (1966) have analyzed examples of this situation. They find that horizontal inhomogeneities in refractivity have little effect on the ray paths at heights above 1 km; however, at low elevation angles and especially in surface ducts, positional errors may be appreciable. In these examples, a radar target at range 300 km will have apparent height error of about 1 km and apparent range error of 20 km.

Recently, a theoretical analysis of this problem has been initiated (Jeske 1973). The theory of convective vapour diffusion has been applied to the development of an offshore evaporation duct, whose depth grows with the length of the offshore wind trajectory.

Ducting over the Timor Sea at 1 GHz has been studied by Barton (1973) in Australia. Refractivity profiles were measured by a microwave refractometer on an aircraft. Ray analysis of these profiles suggested that a tilt in super-refractive layers was responsible for many of the incidents of major increase in signal strength.

4. WAVE ANALYSIS OF DUCTING (PHYSICAL OPTICS)

More precise analysis of radio transmission through the atmosphere is available in full wave theory. Modern computing methods will aid in achieving this goal.

4.1 Formal Expressions for the Fields

The problem of radio wave transmission between a transmitter and receiver above a spherical earth has been developed by Fock (1965, Ch. 16 and 17). Assuming a time factor $e^{i\omega t}$, the electric and magnetic field vectors $\vec{E}$ and $\vec{H}$ are given by

$$\vec{E} = iZ_s \ \nabla \times V\vec{r} - \frac{1}{n^2 k} \ \nabla \times \nabla \times U r \qquad \ldots.(4.1)$$

$$\vec{H} = \frac{1}{iZ_s} \ \nabla \times U\vec{r} - \frac{1}{k} \ \nabla \times \nabla \times V\vec{r} \qquad \ldots.(4.2)$$

Here, $\vec{r}$ is the distance vector with origin at the centre of the earth, k is the free-space wave number, Z_s is the free-space impedance, and n is the refractive index. U and V give the fields of a radial Hertzian dipole of electric and magnetic type respectively, such that

$$U,V = \frac{\exp(-in_o kD)}{(-2i\pi kD)^{1/2}} \int_{-\infty}^{\infty} d\alpha \ \exp(ikD\alpha)\,[g_\alpha^{(1)}(z_L) \ g_\alpha^{(2)}(z_H) -$$

$$R_\alpha^{E,M} \ g_\alpha^{(2)}(z_L) \ g_\alpha^{(2)} \ (z_H)] \qquad \ldots.(4.3)$$

where n_o is the surface refractive index, z_L and z_H are the lesser and greater heights of the transmitter/receiver above ground, $R_\alpha^{E,M}$ are the reflection coefficients of the earth's surface for the electric and magnetic fields, and D is the distance between transmitter and receiver along the earth's surface.

In Eq. (3), $g_\alpha^{(1)}$, $g_\alpha^{(2)}$ are the incoming and outgoing wave solutions for large z of:

$$\frac{d^2 g}{dz^2} = -2k^2 (m - m_o + \alpha) g. \qquad \ldots.(4.4)$$

Here, m_o is the modified refractive index at the surface, and α is a set of characteristic values for these waves. Eq. (1)-(4) apply both within and beyond the radio horizon, for any horizontally stratified m-profile.

4.2 Wave Solutions for Specified m-profiles

Eq. (1)-(4) have been applied to ducting profiles in the lower troposphere, at various levels of sophistication. Because of the complexity of the solutions and the extensive calculations involved, the earliest work used numerous simplifying assumptions. Booker and Walkinshaw (1946) have reviewed the extensive analysis of ducting in the region of the North Sea during the 1940's. The earth's surface was assumed a good conductor, and spherical waves from the transmitter were approximated by cylindrical waves. For a linear m-profile, the series of complex α in Eq. (4) was associated with a number of "modes" of propagation, each with its characteristic wavenumber and attenuation factor. A single mode usually dominates in the diffraction region, and the diffraction field was calculated with little difficulty. However, the field in the interference region required the summation of a large number of modes, - a task that was too taxing for available methods of computation. As a substitute, the interference field was assumed to result from two "modes", one the direct wave between the antennas and the other the wave reflected from the earth. The parallel analysis of transmissions through linear m-profiles, in the U.S.A., has been described extensively in Kerr (1951, Ch. 2). A series of charts was provided for calculating the interference and diffraction fields.

Ducted transmission of radio waves into the diffraction region was included in this early analysis. This implies non-linear m-profiles similar to curves D-G in Fig. 3. Booker and Walkinshaw suggested that each may be approximated by a sequence of linear segments, and the above procedure applied to each segment. However, the summation of the component contributions to obtain the total field was prohibitively laborious, and further consideration was desirable of the contributions by partial reflection at the discontinuities. Instead, four functional forms of m-profile were used.

The square-root profile:

$$(m/m_o)^2 = 1 - 2 K z^{1/2} (z^{1/2} - 2 d^{1/2}) \qquad ....(4.5)$$

The gamma profile:

$$(m/m_o)^2 = 1 - 2 K z - 2 \Delta m [\Gamma\{t(z/h_o)^{2s+1}, t\}/\Gamma(t)] \qquad ....(4.6)$$

The power-law profile:

$$(m/m_o)^2 = 1 - 2K\{ z - (d^{1-s} z^s/s)\} \qquad ....(4.7)$$

The linear-exponential profile:

$$(m/m_o)^2 = 1 - 2Kz + \beta \exp(-\gamma z) \qquad .....(4.8)$$

where K is the lapse rate of m at remote height, d is the "duct width", Δm is the m-deficit, h_o is a scale height, β, γ, s and t are profile indices, and the Γ's in Eq. (6) are the incomplete and complete gamma functions, respectively. Kerr also discusses the bi-linear profile. Some examples of field strength in the diffraction region are computed and presented graphically for these models. Eq. (6) is capable of representing all principle types of single ducts, but simplification to the form of Eq. (7) was required for practical computation.

Improvements in computing methods and in mathematical techniques have extended the analysis to other types of m-profile and to fields in the interference region. Recently, Rotheram (1973) has applied Eq. (1) - (4) to the log-linear m-profile given in Eq. (2.12). Account is taken of the earth's reflection coefficient and refractive index, and the gain pattern of the transmitter. Contributions from as many as nine modes are calculated for the diffraction field. Some difficulties still remain in deriving the interference field. The available solutions to Eq. (3) are the wave analogues of ray optics, and hence are invalid in the neighborhood of caustics; techniques for improving their validity are being investigated.

4.3 Surface Roughness and Surface Obstacles

Comparison between microwave transmission through evaporation ducts and recent theoretical predictions shows that the latter tend to exceed the observed signal amplitudes, in the interference and diffraction regions (Rotheram 1973; Jeske 1973). One reason suggested for this discrepancy is the forward scattering of signal from the rough sea surface, that has not yet been considered in the ducting theory. The existence of multiple paths including terrain roughness scatter is a well-known phenomenon in microwave transmissions (see, for example Thompson 1965; Vogler 1969; Christensen and Gudmandsen 1970). Becker (1972) has reported on theory and experiments to include surface roughness with refractivity inhomogeneities in the fields of radiating dipoles.

Some consideration has been given to the wavelength dependence in surface-roughness scatter (Christensen and Gudmandsen 1970). The Rayleigh roughness parameter (R') relates the roughness scale (h) and the grazing angle (ψ') through

$$R' = \frac{h \cdot \psi'}{\lambda} \qquad .....(4.9)$$

It is suggested that roughness effects increase in importance with decreasing wavelength. While previous experimental studies of surface roughness have been confined to overland transmissions, Straiton (1973) reports that ducting signals at 35 and 70 GHz over the Gulf of Mexico display irregularity that increases with signal frequency; he attributes this in part to the sea roughness.

An interesting extension of this concept has been described by Gjessing (1973). This involves diffraction by a terrain ridge in the presence of surface ducting. The microwave field above the ridge is modified by ducting on the transmitter side, and the signal at the receiver beyond the opposite side is given by the Fourier transform of this field above the ridge. The obstacle gain at the receiver becomes

$$G_o = [(\frac{E_2}{E_1})(\frac{\beta}{2\alpha}) + 1]^2 \qquad .....(4.10)$$

where $E_1(z) = \begin{cases} o \text{ for } z < o \\ 1 \text{ for } z > o \end{cases}$, is the steady component of the field

above the obstacle, and $E_2(z) = E_2 \exp(-\alpha z) \sin(\beta z)$ is the damped sinusoidal component of the field at the same location, and α is the damping coefficient governed by the duct characteristics, $\beta = \lambda/L$ where L is the height interval between maxima in E_2. The gain G_o applies to the direction $\theta = [\alpha^2 + \beta^2]^{1/2}$. Where ducting is a common feature of this type of terrain, a significant improvement in signal transmission to the receiver is realized by discrete location of the transmitter relative to the duct.

5. DUCTING OBSERVATIONS IN CANADA

The winter snow-cover and low temperatures, especially at higher latitudes, introduce persistent characteristics into the refractivity profile near the ground. Belmont (1956) has noted that temperature inversions just above the surface in the Arctic occur 56 percent of the time, mainly in the winter. The chief cause of these inversions is radiational cooling in daytime or at night, since the atmosphere emits long-wavelength radiation as a grey body while the snow-covered surface emits the same wavelengths more efficiently as a black body. More detailed statistics on the incidence of surface temperature inversions in Canada are provided by Munn, Tomlain and Titus (1970). When these are associated with dry air as in the Winter, they provide surface ducting conditions; these occur in South-Western Ontario about 10-35 percent of the time in Winter. But they must be considered along with the surface humidity generally for information on surface ducting. Bean, Cahoon, Samson, and Thayer (1966) estimate that, on the average, surface ducting gradients appear in Canada 1 - 4 percent of the time throughout the year, and that the ducting layer thickness exceeds 100 m for 10-50 percent of the time. The minimum trapped frequency is 3 GHz for less than 2 percent of the time, except in the summer when the incidence may rise to 5 percent.

Four reports on radio ducting in Canada has appeared in scientific journals and research notes. A one-year study of transmissions at 3.2 cm and 10.7 cm over a 27 mi. path near Suffield Alberta was described by Miller, Halbert, Doherty and

Swanson (1947). The path was 60-80 feet above level and homogeneous terrain, remote from lakes and mountains. Temperature and humidity profiles observed systematically at four points along the path were converted to m-profiles. These showed refractivity variations mainly in the lowest 100 m, with horizontal homogeneity along the path occurring infrequently. The signal transmission approached the prediction of diffraction theory more closely as the path refractivity became homogeneous. Signal enhancements always accompanied ground-based inversions. Through observing a line of corner reflectors along the path with radars, infrequent m-inversions at elevated positions appeared to cause "skip" transmissions at isolated targets, with 15-20 db change in transmission level for that target in a time of 1 minute. These were attributed to caustics in the ray analysis of the m-profiles. Short-term forecasting of ducting along the path was difficult because of inhomogeneity in path refractivity, and the strong dependence of transmission upon small refractivity changes.*

The second report deals with 9.7 GHz radar transmissions over Lake Ontario (Hood and Doherty 1957). The 268 marine radar was operated in horizontally scanning mode, while being elevated and lowered repeatedly through a height interval 8 - 228 ft. above water level. Analysis of photographic records of radar echoes showed that ducting occurred more than 50 percent of the time in Summer; ducting was absent in winter. The duct depth varied broadly from 40 ft. in summer to 180 ft. in Spring/Fall. The incidence of ducting showed a diurnal variation

*See footnote page 34.

with maximum in the afternoon. The ducting incidence dropped by a factor of three during rainfall over the lake.

Signal transmissions at 2 GHz over line-of-sight paths near Ottawa and North Bay were described by Hay and Poaps (1959). These paths were between directional antennas some 200 ft. above ground. During a one-year period, signal transmissions were depressed 20-30 db for about 24 percent of the time in summer and less than 5 percent of the time in winter. This "fading" was confined generally to the hours between midnight and 0600 hrs. A ray analysis of special radiosonde profiles indicated that the "fading" was associated with elevated m-inversions some 100 ft. in depth, introducing ray caustics and ray divergence at the receiver antenna. 60 percent of the signal depressions were related to subsidence inversions, 30 percent to inversions of other types, and 6 percent to frontal inversions.

More recently, Doherty (1964) has analyzed 2.7 GHz transmissions overland between Ottawa and Montreal. During one year, he noted that signal enhancements of several db on this 90-mile path were associated with superrefraction or ducting, due to subsidence or advection inversions. Such inversions were found mostly in maritime Arctic air masses, and to a lesser extent in maritime Polar air masses. None were found in maritime Tropical air or continental Arctic air.

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*Profiles of modified refractive index (m) as observed throughout this project are recorded also in JCC/WP/TP Interim Report No. 1 (1 April 1946) and Interim Report No. 2 (undated). Details of the Suffield site are given in figure S-527 of RWPC Report "Tropospheric Project Suffield Alberta" (7 Feb. 1945), RCN.

6. COMMENTS

From the preceeding review, it is clear that the modelling of microwave ducting in the lower troposphere has been achieved with graded success. The most advanced treatment applies to the evaporation duct over an open sea. Here, the current understanding of convective vapour transfer at the surface leads to a log-linear profile of modified refractive index. Microwave transmissions in such ducts are predicted reasonably well into the diffraction region; the ducted signal in the interference region appears to be sensitive to roughness of the sea surface and to turbulent inhomogeneities in the air refractivity. Improvements are being sought in the theoretical model to account for these latter factors. In application of the model, the form of the log-linear m-profile is based upon measurements of temperature, wind and vapour pressure at the sea surface and a few metres above it. Elsewhere, the processes of diffusion above the sea surface are being examined for the purpose of relating the m-profile to synoptic weather systems. It is anticipated that the ducting model will eventually be derived from routine weather observations. At present, the model breaks down in conditions of extreme air stability.

Another ducting model of merit is associated with the persistent elevated advection inversion. As an example, the large scale migration of warm dry air from the Mediterranean area northward over north-west Europe creates this type of inversion. Here, the m-deficit at the 850 mb level provides a measure of the ducting intensity. Thus, regional contours of ducting intensity are derived from routine weather records, and the success at predicting radar ducts 36 hours in advance is comparable with

36-hour weather forecasts.

The complexity of the model increases rapidly with the degree of inhomogeneity of the underlying surface. Both of the above models apply on a regional scale of hundreds of kilometres, where the lower boundaries are generally uniform. This homogeneity deteriorates near coastlines, where experiments indicate that offshore ducting depends upon the length of the wind trajectory. The influence of the land mass may extend 50 miles offshore. Models for this transitional situation are being developed currently.

Overland ducting is characteristically different from the above models. While evaporation ducting may occur occasionally during radiational cooling above saturated land, the more common type is associated with migratory elevated inversions in the m-profile. These generally are related to subsidence of dry air aloft above an anticyclonic area, or to the advection of warm and dry air above moist surface air, or sometimes to frontal intrusions. However, no consistent correspondence has yet been established between details of the m-profile inversions and these synoptic weather features. Ray analysis of vertical m-profiles through these ducts indicates field weakening and caustics in the direction of the receiver, to suggest causes for observed changes in signal transmission. In contrast with surface ducting in which signal enhancements may be as great as 50 db, overland elevated ducting usually leads to signal depression of 20-30 db. Research is required into the details of elevated ducting m-profiles, their horizontal stratification and vertical migration, and their relationship with the synoptic weather features noted above. Little information is available on the microwave frequency dependence in elevated ducting.

One exception to the transient behaviour of overland ducting is the surface radiation duct over snow-covered surfaces at temperatures well below freezing. This is common in the Arctic winter, where dry surface ducts are present over 56 percent of the time. Further study of these ducts and of their microwave transmission characteristics is desirable.

This review suggests that Canadian research on microwave ducting should be considered in three categories. These would apply to three regional divisions; the coastal areas and the Great Lakes, the Arctic regions (especially in winter), and the inland areas of flat and rolling terrain.

(a) <u>For the coastal areas:</u> The extensive research in Europe and the U.S.A., and the surface ducting models being developed there, should be related to the Canadian coastal regions. Radar transmissions over these Canadian areas should be carried out to explore the ducting predictions.

(b) <u>For the Arctic winter regions:</u> Refractivity profiles for this dry air should be recorded over a prolonged interval with the aid of tower-mounted arrays of temperature sensors. These observations will indicate the persistence of microwave ducts, their spatial homogeneity, and their wavelength-trapping characteristics.

(c) <u>For the inland terrain regions:</u> More extensive effort is required in this category than in those above. At least two representative paths for experimental observations should be established, - one with a flat terrain profile and the other with rolling terrain. These paths should provide for microwave transmissions within and beyond the line-of-sight, at two or more microwave frequencies. The choice of frequencies is not critical, but it should embrace the range 1 - 20 GHz since this is of practical importance. These transmissions should have sufficient bandwidth to permit assessment of multi-path delays; observations on the angle-of-arrival of the signal may be useful in this regard. Refractivity profiles should be observed with fast-response sensors at several stations along the signal path, for ray analysis and for air-stability assessment. These also would provide an indication of horizontal inhomogeneity in air refractivity. An important aim of this work would be the relation of m-profile characteristics to synoptic weather features, as a step in the development of a ducting model. At a later stage, wave theory and ray analysis should be applied to this model to predict the microwave transmission for various positions of a transmitter and receiver relative to the duct.

A recent survey of microwave communications experience in Canada supports the findings reported in Section 5.* For the desired transmission reliabilities exceeding 99.99 percent, frequency and space diversity usually are necessary. Rayleigh fading distribution apparently is not observed on many of these paths, and other aids to reliability design are desirable.

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*Report by Petrie Telecommunications Ltd., Ottawa, to the Communications Research Centre, Ottawa, March 1974.

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