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The Measurement of Tropospheric Refractive Index Relevant to the Study of Anomalous Microwave Propagation — Review and Recommendations

by
B. Segal

CRC REPORT NO. 1387

Ottawa, June 1985

Government of Canada
Department of Communications

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Canada

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SUMMARY

The physical properties of the earth's atmosphere constitute an important factor in determining the nature of radio wave transmission from one location to another on the earth's surface. This report presents a summary of various attempts at observing the refractive index structure in the lower levels of the atmosphere where its impact on radiowave propagation is greatest. It also contains a review of different meteorological techniques and instrumentation for studying the troposphere and discusses possible methods for injecting these instruments into the region of interest. In addition to the references considered explicitly in the main body of the report, a substantial bibliography is included. This bibliography is the result of a search of the literature dealing with numerous theoretical and experimental aspects of anomalous microwave propagation.

It is hoped that this report will serve as a point of departure for considerations of a renewed experimental and analytical program aimed at improving our understanding of the interactions between the sometimes subtle climatic and temporal changes in the troposphere and the transmission of microwave signals over terrestrial links. It is envisaged that such a program, if it is to be fruitful, would involve the cooperative efforts, resources and expertise of government (CRC), industry (carriers) and the universities. A dual rôle is envisaged for CRC; namely, that of sponsoring and co-ordinating the different interests and activities of outside researchers, and that of providing support in the form of measurement and analysis of the tropospheric meteorology.

As this report makes clear, a good deal of research and development remains to be done in the area of improved meteorological instrumentation. It is hoped that some university departments will find this a suitable opportunity to undertake development of improved meteorological instrumentation, either alone or in cooperation with CRC.

1. INTRODUCTION

The propagation of radio waves between a transmitter and a receiver is determined by the nature of the earth's surface (curvature, roughness, conductivity, *etc*) and by the properties of the intervening medium – the troposphere. Even if the earth cannot be entirely ignored in this context, its direct influence is generally quite stable. Attenuation of microwaves by rainfall is well understood; excellent prediction statistics exist for Canada. What remains, therefore, is a proper understanding of propagation under so-called 'clear-air' conditions. A complete and detailed description of the tropospheric refractive index should, in principle, allow one to determine the propagation behaviour through the medium.

In practice, the problem is far from straightforward. If all of the relevant meteorological information were known, the very complexity of the situation would render it intractable. And we currently lack a clear understanding of the underlying meteorology. A very strong need therefore exists for a better understanding of the tropospheric properties leading to frequency-independent (flat) fading, frequency-selective (multipath) interference, ultra-long group delays, *etc* and for models which suitably employ this information.

This report assembles and loosely examines the literature relating to refractive multipath propagation in the hope that it will help to develop a little expertise on the subject and to qualify any ideas and expectations with respect to new experimental programmes. An effort was made to record all relevant experimental and theoretical efforts available in the literature. A few comments, however, derive from personal experiences of the author during the mid-1950s while employed at the Defense Research Telecommunications Establishment (DRTE), later reorganized as part of CRC. Unfortunately, most of the details of the pioneering work on refractometer development and tropospheric measurement being performed at that time were not published or were contained in DRTE reports long since out of print.

2. TROPOSPHERIC REFRACTIVITY STUDIES

While the nature and the objectives of an experimental study would almost certainly change during the course of the experiment and/or subsequent analysis, it is important to list some of the questions relating to anomalous propagation which can be formulated in advance of any specific reseach programme. The following is such a list in very broad terms; each of these questions can be subdivided into items of finer and finer detail. The suitability and relevance of these questions is restricted, of course, by the fact that there is, at present, no terrestrial microwave radio experiment or test link which might provide both the problems and the data to be used in developing a realistic radio-meteorological model.

2.1 ONE-DIMENSIONAL TROPOSPHERE

If the atmosphere is assumed to be horizontally uniform,

(a) Can we identify particular refractive features with particular types of propagation anomaly? For example, is there a 1:1 relation between multipath propagation and high level or low level ducts in a particular location, *etc*?

(b) Where clear 1:1 relations are *not* apparent but there is a strong diurnal characteristic associated with the observed propagation behaviour, can we identify a consistent diurnal refractive condition?

(c) Are periods of anomalous propagation regularly associated with synoptic weather conditions, *eg,* fronts, inversions, absence of winds?

(d) Are anomalous propagation conditions more likely to be associated with refractive discontinuities or very extreme gradients or are they more closely associated with relatively gentle layers of modest deviation?

(e) Are there any cases of anomalous propagation with no apparent refractive irregularities? What is the refractive profile like at these times?

2.2 TWO/THREE-DIMENSIONAL TROPOSPHERE

(f) What is the horizontal extent of different refractivity structures? Is there a statistical correlation beteween the refractive magnitude or the vertical dimension of a particular feature and its horizontal dimension?

(g) How does the vertically smoothed refractivity profile* vary with horizontal range?

(h) Are there any discernible tilts or waves in the refractive index profile? Are these rare or common occurrences? Over what types of terrain, season, *etc*?

2.3 ANALYTICAL

(j) To what extent can experimental results be explained *consistently* by ray tracing techniques?

(k) Assuming that there is some degree of horizontal variation, at least in fine detail, are the vertical refractivity profiles, $N(h)$, best averaged spatially or temporally during quiet conditions? – during anomalous periods?

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* Note, implicit in the bulk of this report are the anomalous effects induced by thin layers and/or extreme negative vertical gradients in refractive index. Large positive gradients (sub-normal refraction) also lead to difficulties and possible disruption of terrestrial microwave signals if they extend over large distances. This important subject deserves further study in its own right, especially in Canada. A better understanding of horizontal uniformity would help to establish a proper path-length relation for effective 'k' values. This in turn would result in more legitimate application of the Canadian refractivity atlas [Segal and Barrington, 1977]. In spite of its importance, this refractivity-related problem is not discussed further in this report.

3. BACKGROUND

In this chapter we review briefly some of the radio-meteorological experiments and analyses which have been undertaken in connection with microwave propagation over terrestrial links. These attempts to observe and interpret the meteorology of the lower troposphere are divided into two sections. In section 3.1 we consider those investigations based on either direct or indirect measurement of the tropospheric refractive index. In section 3.2 we will examine some of the investigations which are based on the study of other meteorological predictors.

3.1 STUDIES OF THE TROPOSPHERIC REFRACTIVE INDEX

3.1.1 Vertical refractivity and radiowave propagation

Attempts to relate the tropospheric refractive index to details of anomalous microwave propagation behaviour date back at least three decades to the pioneering work of Ikegami at NKK in Japan. In English, his results were published in a classic series of papers as late as 13 years after the original observations were made [Ikegami, 1959, 1967; Ikegami *et al*, 1966, 1968]. Despite some difficulties, this early work remains a very important one.

The 1967 paper by Ikegami is an expansion of his earlier publication [Ikegami, 1959]. Propagation measurements were made over 55 km horizontal and slant links between the same geographic locations. Meteorological observations were taken at fixed positions on the transmitting tower.

The emphasis in this pioneering work was on the direct application of ray tracing. Without the aid of electronic computers, Ikegami was forced to approximate the $N(h)$ profiles by means of piecewise linear segments. By deriving analytic solutions for propagation through such profiles he was able to define certain 'critical' rays, *eg*, those grazing the surface of the earth or those reflected at the boundaries of a refractive layer, *etc*.

By this means he determined the regions into which there could theoretically be no propagation or where multiple ray paths intersected as a result of low-lying ducts. These regions should, in principle, produce large signal attenuations and rapid fading.

A detailed explanation of the received field was not possible for a variety of reasons. Firstly, the meteorological measurements were made only at the surface, at 13 m altitude and at 20 to 30 m intervals thereafter [Ikegami *et al*, 1966]. This would certainly have resulted in a 'smearing' of the details of the actual $N(h)$ profile. Approximations in the profile shape which Ikegami required for analytic purposes would have resulted in a further degradation of the atmospheric model. Secondly, as mentioned, all meteorological observations were made at one end of a fairly long circuit. Thirdly, the analysis employed by Ikegami completely ignored the effect of ground reflections although these would have been present on both of the propagation links. Finally, the results, while interesting and instructive, were largely inconclusive because only one night's data were examined in depth, and that for a selected case of "a simple single duct".

What was found, however, was that the onset and duration of attenuation coincided reasonably well with the times for which the observed $N(h)$ profiles predicted either multiple ray propagation or no propagation to the approximate location of one or other of the two receiving antennas. For the entire nine days of test data, collectively, there was a qualitative correlation between the mean propagation loss, the 5-minute fading range and the occurrence of a duct at or slightly below the lower of the two antennas of a link. (The data suggest a secondary height of influence for the slant path in the region below the upper antenna).

Although Ikegami, like so many workers since, devoted most of his attention to examining the influence of tropospheric ducts on the received signal it is of historic interest to note that he recognized that multipath interference could also result from underlying subrefractive layers.

Ikegami likewise investigated the effect of other refractive inhomogeneities on the convergence and divergence of adjacent ray paths. Thus, he first illustrates the contours of enhancement and attenuation resulting from a simple underlying duct. Again, instantaneous comparisons with observation were impossible; however, he argues that the fading pattern observed as a function of time corresponds well with the oscillations in height gain expected as a duct is displaced vertically.

In his conclusions, Ikegami argued that fading caused by refractive layers is of two types. Firstly, there is the interference resulting from multipath propagation. Secondly, there is the enhancement and/or attenuation caused by convergence and divergence of ray bundles. The former effect is very frequency selective and is caused, it is claimed, by an underlying duct or a subrefracting layer. The latter effect, which is not frequency dependent, results from non linearities in the refractivity gradient profile.

In fact, the two are different manifestations of the same or closely related meteorological situations. For atmospheric multipath propagation to occur there must, of necessity, be some ray convergence. The converse, however, does not usually hold. Although the occurrence of multipath propagation is often taken to imply the presence of ducts, neither duct nor subrefractive layer is essential. Atmospheric multipath can occur under a variety of conditions, a fact that does not always appear to have been appreciated (see Fig 1).

Other scenarios may also be envisaged for multiple ray propagation, *eg*, surface reflection or reflection from a high-level refractive discontinuity, or by scattering or leakage into and out of a duct well removed from the propagation level.

Continuing in the same philosophical vein as Ikegami, Boithias [1979] attempted to arrive at some design guidance with respect to deep flat fades and/or multipath fading. The work was related very vaguely to some observations made at 6 GHz in Senegal.

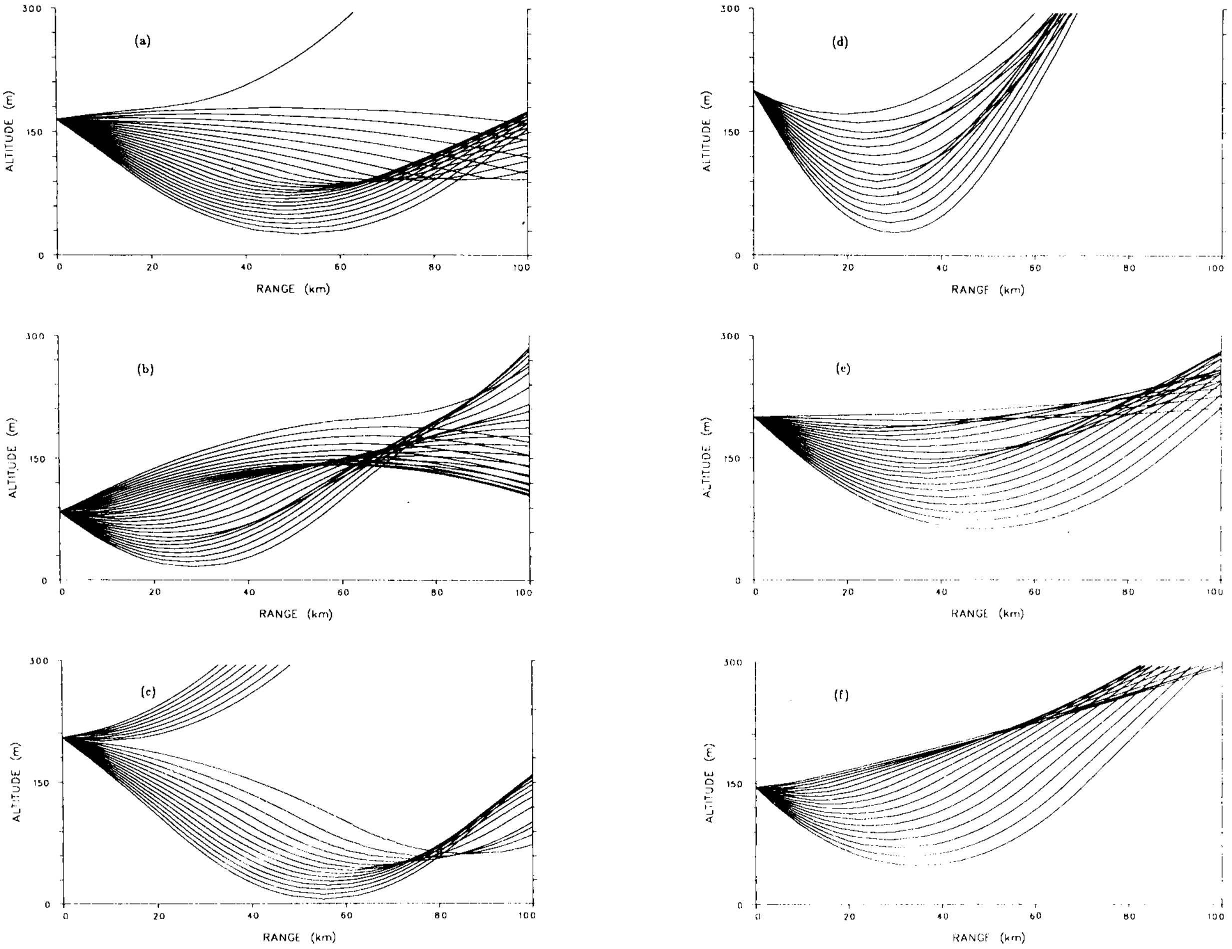

Figure 1. Examples of atmospheric multipath propagation under a wide range of tropospheric conditions:

(a) antenna within the upper portion of a duct layer, *ie,* the region with a ducting gradient.

(b) antenna located in a duct base, *ie,* in the extension below the level of the ducting gradient.

(c) transmitting antenna located above a duct.

(d) antennas immersed in a completely sub-standard tropospheric refractivity profile.

(e) a totally superrefractive troposphere.

(f) source in a uniform region of normal refractivity below a superrefractive layer.

Using computer-plotted tropospheric ray traces, he reaches several conclusions regarding the heights and ranges at which deep fades are possible in the presence of uniform surface ducts. Unfortunately, ducts are not always – nor even generally – ground-based, nor is the troposphere sensibly uniform during periods of anomalous propagation.

While his conclusions deal exclusively with the problem of flat attenuation, one interesting result which flows from this type of analysis – but which Boithias has not picked up – is that an attempt to eliminate multipath by reducing ground reflections (by site shielding, for example, or by the use of narrower beam antennas) will result in an increase in the probability of flat fading.

While the conclusions themselves are of little general value, the work is suggestive of how ray tracing might be employed to analyze a situation if suitable data were available regarding the refractive environment – at least if the complexity of the actual profile can be reduced to its essential elements.

Unfortunately, the open literature contains very few cases where detailed tropospheric refractivity data are legitimately and successfully applied to the explanation of anomalous propagation. Thus, Von Hagen [1967] discusses the construction of a Hay UHF refractometer/thermometer sounder which was carried aloft by a nine-foot tethered balloon. The package was used to obtain vertical $N(h)$ profiles beside the Bay of Fundy in conjunction with the NB-NS microwave link. A very complex micro-structure was evident; ducts were extremely frequent, but no meaningful analysis was performed.

Another important work of questionable merit is that of Schiavone [1982a]. This is one of a continuing series of papers to be considered later. Briefly, AT&T Bell Laboratories has installed very limited instrumentation on a 6 GHz receiving tower in Palmetto, Georgia. In this particular study, carried out during the summer of 1981, the vertical refractivity profile was measured by means of temperature and dew point instruments suspended from a tethered balloon operated by the Georgia Institute of Technology. The vertical resolution was claimed to be between one and six metres.

Of a total of 40 hours of balloon operation (10 days x 4 hours/day), 16 hours coincided with periods of fading activity. For these four days the signal extremes were selected for further analysis. In two instances, there were very rapid signal strength fluctuations while in the other two there were slower fluctuations. The former also displayed smaller mean signal deviation from quiet levels but larger standard deviations than the latter. Schiavone [1982a] did not use his refractivity profiles directly but examined, instead, the rate of change in refractive gradient, $d/dh(dN/dh)$. To this end he used the values at 50 m(!) intervals to produce a very coarse profile of the second derivative of refractivity at 50, 100 and 150 m altitude.

For two cases the sign of the second derivative remained more or less constant over this interval and the author argues (qualitatively only) that this condition produces the refractive focusing needed to explain the observed fades. No explanation is offered for the other two cases.

Most damning, however, is not the fact that only two minutes out of 16 hours of data have been "explained" but the fact that the simple argument presented is insufficient in the predictive sense. Examining some of the other $N(h)$ profiles in the manuscript suggests several instances where the same type of variation is not accompanied by strong signal focusing.

In part, the inadequacy of this work is the result of insufficient analysis. More precise information on the refractive structure could have been helpful (with proper analysis).

3.1.2 Horizontal refractivity inhomogeneities

One consideration which is potentially important for propagation analysis under certain meteorological or geographic situations is that of horizontal inhomogeneity in the refractive index. The simplest realistic form of such inhomogeneity is that of tilted refractive surfaces. Again, little is known about the occurrence of such atmospheric tilts; experimental observations would be extremely valuable.

Martin and Wright [1963] describe a ray tracing technique which they apply to the problem of radar propagation in the presence of tilted layers. Their calculations suggest that the effect of typical or average refractivity gradients in the horizontal plane would be entirely negligible on terrestrial links. Much larger horizontal gradients can be expected, however, across weather fronts or at land/sea boundaries. Schleher [1982], for example, summarizes an intensive search for tilted refractive surfaces off the Florida coast. During the sunrise period, numerous instances were recorded of strong ducts having tilts (rising off-shore) of up to 1.5 degrees (26 mrad). It is postulated that radar (or other) signals beamed at up to two degrees elevation angle could be deflected to a horizontal trajectory whence they might couple into a low-lying evaporation duct.

Barton [1973] presents probably the most interesting and encouraging application of refractive data to propagation since the pioneering work of Ikegami. As in the two preceeding cases, the investigation was directed to the study of anomalous radar operation, in this case off the coast of Australia. The analysis, however, is suggestive of what might be achieved.

A conventional microwave refractometer carried aboard an RAAF aircraft was used to take four two-dimensional profiles of refractive index (up to 1500 m altitude and 200-400 km range). Layers of ducting gradients were observed at all ranges, with lapse rates regularly exceeding 1500 N/km. Following only the ducting layer as a function of range, distinct atmospheric tilts were evident. There was no consistent pattern in the layer slope. Significant changes were noted in both the layer thickness and refractivity lapse rate as a function of position.

The ray tracing procedure of Martin and Wright [1963] was then used to examine the possibility of wave trapping. In several instances the tilted layers are seen to be directly responsible for ray trapping and for anomalous long-range echoes. Because of the long flight paths employed in this study, it was not possible to separate the temporal from the spatial variations entirely. Better tropospheric definition could be hoped for over a typical communications link.

3.2 PROPAGATION STUDIES – MISCELLANEOUS WEATHER DATA

Several studies of anomalous clear-air propagation have been carried out in conjunction with meteorological measurement programs which do not include the determination of the tropospheric refractivity profile. Such programs may point to some of the basic processes that give rise to fading but their immediate utility is unclear. A total understanding of the problem demands both refractivity and synoptic weather data.

Bundrock and Murphy [1984] describe a $2\frac{1}{2}$ year broad-band radio experiment over a 36 km land path. Multipath fading was observed during well-defined periods in the early morning hours. Generally, the events occurred in the presence of ducts or superrefractive layers which formed beneath nighttime temperature inversions and were lifted into the propagation region at sunrise.

Two propagation mechanisms were noted. In the first, strong ray divergence or defocusing in the upper portion of the layer reduced the direct signal to a level comparable with the ground-reflected component, thus resulting in strong frequency-selective interference. As a result of the low value of refractivity in the divergence region the ground-reflected ray exhibits a large relative delay. On other occasions, defocusing of the tropospheric ray was noted along with an apparent reduction in the delay of the reflected component. Since the investigators lacked suitable refractivity profiles, they were unable to propose a meteorological model for this mechanism.

This is an example of a fine, carefully conducted propagation experiment severely hampered by the absence of refractivity data and associated analysis.

As noted earlier, Bell Labs is currently engaged in a propagation study with limited meteorological input. The aim of this program appears to be one of reaching a general, statistical explanation of anomalous propagation rather than a detailed, specific one. In Schiavone [1981], temperature, humidity and winds were measured at four levels, including the ground, in conjunction with a 6 GHz, 57 km propagation test. During the summer, fading was found to be associated with a stable troposphere as indicated by positive temperature gradients (inversions) while large daytime lapse rates, indicative of an unstable atmosphere, were associated with normal propagation conditions. These conditions are very well known. During autumn, however, it is postulated that the occurrence of significant fading is associated with the direction (sic) of the 500-mbar winds.

In Schiavone [1982b] an attempt is made to explain – in a very qualitative manner – the diurnal fading pattern in terms of changes in the moisture content of the atmospheric boundary layer.

Schiavone [1983a] gives us yet another qualitative discourse, this time relating the seasonal changes in fading behaviour with seasonal changes in the air mass (over Georgia). Statistically, of nine general weather parameters, the best fading correlation was obtained with respect to the logarithm of the local 4:00 am surface wind speed.

4. DETERMINATION OF ATMOSPHERIC REFRACTIVITY

The refractive index, n, of the atmosphere may be expressed in the form

$$n = 1 + 10^{-6} N \tag{1a}$$

where the refractivity is given by

$$N \approx 77.6(P/T) + 3.73 \times 10^5 (e/T^2) \tag{1b}$$

and P is the total gas pressure (mbar), e is the water vapour pressure (mbar) and T is the gas temperature (K) [Smith and Weintraub, 1953].

The partial pressure due to water vapour may be deduced from measurements of temperature and relative humidity or dew point. Atmospheric refractivity may therefore be determined by making independent measurement of temperature, pressure and relative humidity (or its equivalent), or by the use of a refractometer to measure n directly.

Differentiating (1b) we may examine the sensitivity of N to changes in both e and T. Except in tropical regions, the water vapour pressure, e, varies dramatically with time (seasonally and diurnally). Relative humidity, R, comes much closer to representing a regional climatic parameter. For this reason, and because R is better appreciated by the non-meteorologist, this somewhat unorthodox quantity has been chosen to illustrate the functional dependence of refractivity on atmospheric water vapour in Figure 2.

Figure 2a shows the sensitivity of N with respect to R as a function of temperature. The results are qualitatively what one would expect. At very low temperatures, where atmospheric moisture is slight, a change in R has a small effect. For higher temperatures, we find sensitivities of the order of 1.0-1.5 $N/\%R$. Thus, a sudden change of 10% or so in R on passing through a layer discontinuity would produce a significant change in refractive index.

In Fig 2b the sensitivity of N with respect to temperature is shown as a function of R with temperature serving as a parameter in this case. Here the sensitivity is always large, never falling in magnitude much below $1N$/deg C. The crossover of the various curves is worth noting. For very low R, the sensitivity of N is greater at low ambient temperatures. At higher R, however, the sensitivity is far greater for high temperatures. The prevalence of surface ducting over warm bodies of water and during nighttime continental cooling at high latitudes in part reflects these dependencies.

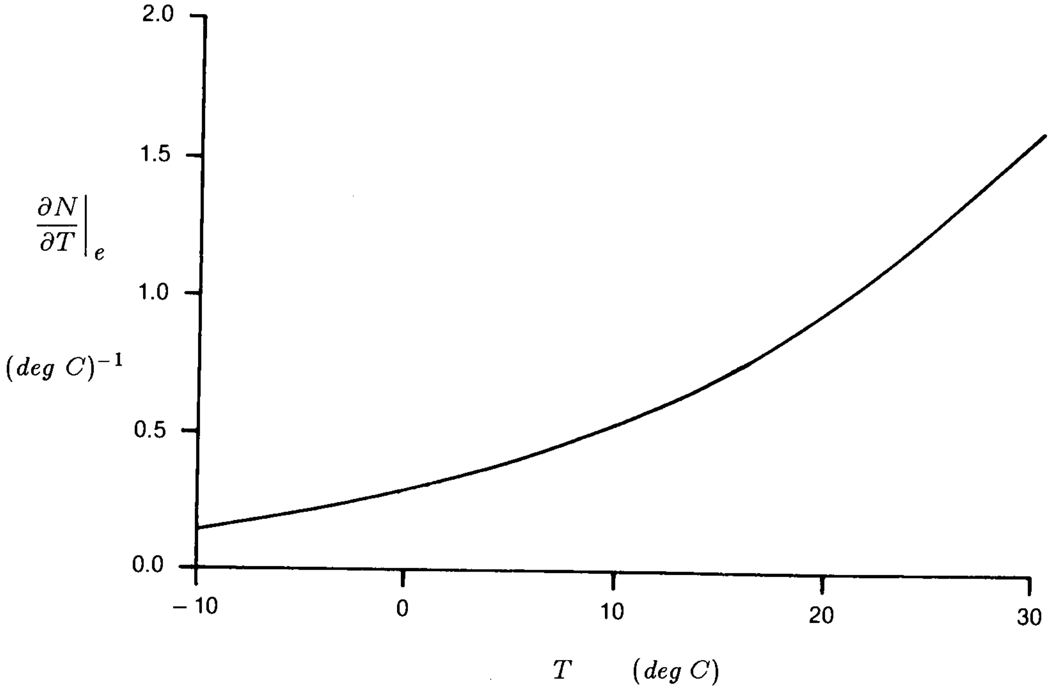

Figure 2a. Variation of atmospheric refractivity with changes in temperature for fixed water vapour pressure.

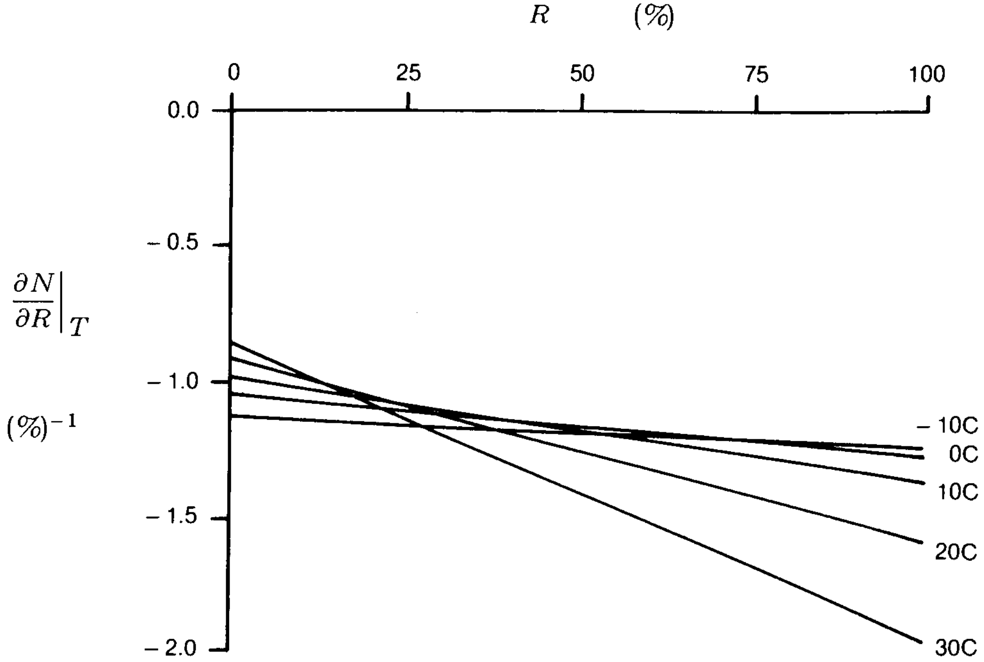

Figure 2b. Variation of atmospheric refractivity with changes in relative humidity at constant temperature.

4.1 REFRACTIVE INDEX FROM COMPONENT ELEMENTS

4.1.1 Temperature

The current choice for the temperature sensor in the present application is the thermistor [Govind, 1975; Gangopadhyay *et al*, 1974; Venkiteshwaran *et al*, 1982] although cases exist where more classic methods have been employed, *eg*, mercury in glass [Ikegami, 1966] and platinum resistance wire [Hinzpeter, 1973; Barletti *et al*, 1975]. Platinum wire thermometers have also been used to supplement airborne refractometer measurements [Lane, 1965].

While the platinum resistance thermometer may offer the ultimate in precision in a laboratory environment, it also carries with it several serious impediments. The fragility of the final wire (only several micrometres diameter after mounting and acid etching) makes handling a delicate matter. Operation outside of a helicopter or airplane might involve considerable trial and error to develop suitable attachments. Most importantly, however, the device is inherently velocity sensitive. In fact, the hot-wire thermometer is one of the standard probes for atmospheric turbulence studies [Ali, 1975].

The advantages of the thermistor are its ruggedness compared with the platinum wire thermometer and its speed of response relative to the mercury in glass thermometer. In addition, a wide variety of thermistor elements is commercially available, obviating the need for time-consuming laboratory development of new techniques. Over the short term, the thermistor exhibits a stability comparable to the platinum thermometer. Long-term drift is not a serious concern for anomalous propagation studies. Thermistors with time constants of the order of one hundred milliseconds were common years ago; the current state of the art is undoubtedly better.

4.1.2 Pressure

Unfortunately, the measurement of atmospheric pressure is less straightforward than the corresponding temperature determination.

Calebotta [1973] described a family of commercially manufactured transducers (National Semiconductor) in which four piezoresistors on a single silicon chip are used in a Wheatstone bridge configuration. An internal temperature sensor may be used in a temperature-compensation circuit. Alternatively, the sensor may be used to control a constant-temperature heat sink, or to record the substrate temperature for subsequent data correction. Another commercial solid state transducer (Sen Sym) employing the same principle as the National device but somewhat simpler in design has more recently been outlined by Gupta [1984].

The traditional anaeroid capsule, the warhorse of all routine, expendable radiosonde packages, has been used in more demanding applications as well [Hinzpeter, 1973]. Ovarlez *et al* [1974] and Govind [1975] independently developed "improved" versions of the anaeroid barometer in which the cell was completely unloaded by pointers, contacts, potentiometers, *etc.* Instead, the capsules were mounted above fixed metal plates in a capacitor configuration. This approach has been further developed and is commercially exploited in a series of small, mechanically rugged, high-precision transducers (Setra Systems).

4.1.3 Humidity

The measurement of relative atmospheric humidity has seen a wider variety of instruments and techniques than perhaps any other commonly measured meteorological variable. It probably remains one of the more difficult quantities to measure with great accuracy outside of the laboratory.

Among the earliest techniques for measuring relative humidity is that of measuring the changes in the physical dimensions of a thin fibre. The material may be of natural or synthetic origin. Human hair, in particular, has long served for this purpose. As superior methods have been developed, nylon has generally replaced hair as the sensing element in those non-critical applications where the technique is still exploited. The accuracy of fibre hygristors is generally low and when designed for maximum speed and sensitivity the fibre element is mechanically fragile.

Hygroscopic salt solutions have been exploited as the basis of a variety of useful humidity-measuring instruments. In the Dunmore cell, a metallic salt (lithium chloride) is evaporated onto a ceramic substrate. By incorporating a fine bifilar winding, the device permits a direct electrical determination of R as the resistivity changes due to vapour absorption by the salt. While these cells have long been used for routine measurements, their limited accuracy (5-10%), range (typically spanning only 15-20% in R per cell) and speed (time constant of several seconds) are inadequate for contemporary tropospheric research. They are also very susceptible to contamination by dust and water and require frequent calibration.

The Pope cell, a device similar to the Dunmore cell uses a sulphuric-acid-treated polystyrene film as base. This cell exhibits a wider operating range than the lithium chloride one but shares its limitations with respect to accuracy and speed.

Another device which relies on the hygroscopic properties of lithium chloride is the saturated dew-point sensor. Here a salt film is carefully heated until the rates of evaporation and condensation at the surface are balanced. The temperature at which this takes place is a function of the ambient atmospheric water-vapour pressure. The method, though accurate, is not suitable for measuring rapid fluctuations.

Another electrochemical device for measuring R is the electrolytic hygrometer in which a film of phosphorus pentoxide absorbs water vapour which is then dissociated into hydrogen and oxygen at a rate which is a measure of the absolute humidity.

Thin films of carbon with hydroxyethyl cellulose have been widely used as humidity sensors in the expendable radiosondes operated by Environment Canada and other agencies. The electrical resistance of the film is a measure of the relative humidity of the air passing over the element. As with the devices mentioned above, these hygristors are relatively slow in response.

Chleck [1979] used an aluminum oxide moisture sensor for upper tropospheric sounding. In that device, a thin gold film was evaporated onto an aluminum surface to produce a simple parallel plate capacitor. Water vapour absorbed by the oxide dielectric through the gold layer altered the admittance between the gold and aluminum electrodes. The time constant was several tens of seconds.

A classic technique widely used for determinating R is the wet/dry bulb thermometer, although bead thermistors would likely be used as the temperature elements today. Wiederhold [1975a] suggests that the wet/dry thermometer is most accurate near 100% relative humidity. On the other hand, the wet/dry technique becomes problematic at very low R and/or at dew-point temperatures below 0°C. Of course, the water vapour pressure is quite low at such times. Compared with the instruments discussed above, the wet/dry thermistor pair exhibit a relatively fast response. Nonetheless, while the bare thermistors may have aspirated time constants of several tens of milliseconds, the addition of a wet wick may increase this by several orders of magnitude (*eg*, to 10 sec or more). Hall and Gardiner [1968] go so far as to suggest that the dry element should be artificially loaded to increase its thermal lag to match that of the wet sensor. The reasoning behind this suggestion is not clear.

Wet and dry bulb thermometers have been used in tropospheric refractivity studies in warm regions of the world and/or where a simple, inexpensive instrument was necessary. Thus, we find their use by Crozier [1958] in California, Hall and Gardiner [1968] in the UK (summer only), Kapungu *et al* [1981] in Nigeria and by Venkiteshwaran *et al* [1982] in India.

The condensation dew-point sensor is an electro-optical device of high precision and reliability under ideal conditions. A thermoelectric device (*eg*, a Peltier junction) is used to cool a small, optically reflective surface. A photocell monitors the specularly reflected light from a LED or other source. As the surface passes through the dew (frost) point temperature, moisture droplets condense (freeze) on the surface, interrupting the reflected light beam.

Roulleau and Poc [1978] used a sophisticated form of frost-point hygrometer for stratospheric measurements. The response time of that device was several minutes. No comprehensive data have been located for low altitude operation.

Regtien and Makkink [1978] improved on the dew-point sensor by greatly reducing its size and by replacing the optical detector with a capacitive circuit etched onto the surface of a silicon chip. The resulting detector was claimed to be less sensitive to particulate contamination. Precision of that device was very good but no data were given with regard to response time under operational conditions. Vetrov and Katushkin [1973] discussed some theoretical aspects of capacitive dew-point sensor design.

For the measurement of R with a higher degree of precision than was possible by most other techniques, Sargent [1959] employed a modified Birnbaum refractometer (see §4.2.3) as a recording hygrometer. The apparatus was developed more or less specifically for use in calibrating other microwave refractometers. In the laboratory environment the accuracy, sensitivity and stability were sufficient for its proposed use as a secondary reference standard. Its configuration, however, was not suitable for rapid, small scale measurement. A refractometer was also used by Stokesberry and Hasegawa [1976] for determining relative humidity. In propagation studies, the relative humidity profile might be derived as a byproduct of refractometer operation; however, that would never be its primary meteorological objective.

Newer techniques are today being exploited for ultra-precise moisture measurements. Agriculture Canada has several IR-laser CO_2 detectors at least one of which may have been adapted for water vapour measurement (private communication). One of the two instruments can be used for rapid, small-volume gas analysis; the other is apparently a larger volume sampler. No details on this class of instrument or on these specific devices are available at this time.

4.2 REFRACTOMETERS

In the refractometer – an instrument for directly measuring the refractive index of the troposphere – a sampling element is exposed to the atmosphere in a manner which determines the resonant frequency of that element or of the circuit in which it is situated. Originally used to determine the dielectric permittivity of gases, the technique was extended to radio-meteorological studies during the 1950s and 1960s.

For tropospheric research three basic forms of the refractometer can be distinguished according to the frequency range in which they operate. Thus, we recognize the hf, the uhf and the microwave refractometer.

4.2.1 The hf refractometer

In an attempt to come up with a cheap, lightweight device for tropospheric studies, Hay developed the hf refractometer, initially at DRTE and later at the University of Western Ontario [Hay *et al*, 1961]. In this instrument, the open metal plates of a capacitor exposed to the atmosphere determines the operating frequency of an hf oscillator. Despite its apparent simplicity, the hf refractometer has failed to attract adherents other than Hay and his students who have successfully used it to study small-scale temperature and humidity fluctuations near the ground.

Since changes in the atmospheric refractive index produce corresponding changes in the resonant frequency of the refractometer, the sensitivity (precision) of the instrument is directly related to the circuit Q. Hence, its sensitivity will almost certainly be less than that of an uhf or microwave refractometer employing a carefully designed resonant cavity.

The simplicity of the hf refractometer is further marred by its much greater sensitivity to moisture hygroscopically condensed on the capacitor plates. Coating the surface with beeswax may reduce this problem but it is likely to aggravate the problem of contamination by dust and insects.

4.2.2 The uhf refractometer

Like the previous device, the uhf refractometer was developed as a simple, inexpensive instrument and has been used by only a single group of workers situated, in this case, at the University of Texas [Cogdell *et al*, 1960; Deam, 1962; Deam *et al*, 1968; Straiton *et al*, 1967, 1968]. The instrument sensor consists of a vented coaxial cavity operating at a frequency of about 400 MHz.

The original cavity [Deam, 1960] consisted of a pyroceram outer cylinder with a fused quartz centre rod, both of which were painted and silver plated. The cavity had an unloaded Q of approximately 2000. The resonant frequency exhibited a temperature coefficient of the order of 1.8×10^{-6}/deg C, surprisingly large in view of the low coefficient of expansion materials used; an uncompensated Invar cavity exhibits a temperature coeficient closer to 1.0×10^{-6}/deg C.

The absence of any widespread popularity of the uhf refractometer is undoubtedly related to the physical limitations imposed by its operating frequency. The Deam half-wave cavity was approximately 33 mm in diameter and 406 mm long. The device thus "samples" a larger volume of air than desirable. This is especially important when used to study the atmospheric structure function (small-scale turbulence). Of greater importance to studies in support of tropospheric propagation, the intrinsic ventilation through the cavity would be low due to the large length to diameter ratio, approximately ten times the equivalent ratio for a typical microwave refractometer cavity. The device would therefore be restricted to mounting aboard a conventional propellor-type aircraft with the cavity axis aligned in the direction of motion.

4.2.3 The microwave refractometer

For several decades the warhorse of tropospheric refractivity studies has been the microwave refractometer. The techniques involved were first used to study the dielectric properties of gases and were only later extended to atmospheric and radiowave propagation research. Canada was the first country to engage in research in this field outside of the U.S. The work done here during the 1950s focused largely on the practical problems of cavity fabrication although a refractometer of sorts was built and, if the author's memory serves, a single recording of atmospheric fluctuations was made at a fixed location. This and other programs of tropospheric research were unfortunately terminated shortly thereafter in favour of rocket-launched studies of the lower ionosphere.

4.2.3.1 *Design*

Two basic forms of the microwave refractometer were introduced almost simultaneously [Birnbaum, 1950; Crain, 1950]. With recent developments in microwave technology, however, a number of very significant advances have been made. In all practical versions of the instrument, a right-circular cylindrical cavity operating in the TE_{011} mode near 9.4 GHz is exposed to the atmosphere by means of suitably vented end plates. The resonant frequency of the cavity is then employed as a measure of the refractive index.

A major problem to be solved by one means or another relates to the measurement of this resonant frequency with the necessary accuracy. Because the velocity of propagation inside the cavity is inversely propotional to the refractive index, we have

$$\begin{aligned} f_{res} &= v_{cav}/\lambda \\ &= (c/n)/\lambda. \end{aligned} \tag{2}$$

Thus,

$$df_{res} = -\frac{c}{\lambda} \cdot \frac{dn}{n^2} \tag{3a}$$

$$\begin{aligned} df_{res}/f_o &= -dn/n_o \\ &\approx -10^{-6} dN. \end{aligned} \tag{3b}$$

To reliably measure a difference of 1 N-unit one must therefore be capable of determining the resonant frequency with a precision of one part per million. Until recently, this measurement was always accomplished indirectly. Since it is the fluctuation, dN, which is of greatest interest, the corresponding fluctuation, df_{res}, was measured by comparison with a stable 'reference' frequency as close as possible to f_o, the value of f_{res} at the earth's surface.

In the Crain [1950] refractometer, two cavities of similar dimensions were used to stabilize the frequencies of two independent oscillators. The reference oscillator cavity was evacuated and sealed. The outputs were mixed and the difference was fed through a conventional 10.7 MHz IF amplifier and discriminator circuit.

Instead of measuring the frequency difference directly, Birnbaum [1950] effectively transposed the problem into the time domain. A single variable-frequency oscillator was swept over a suitable range and the resonant output spikes from each of the two cavities in turn were used to trigger a bistable multivibrator. The precision of refractivity measurement was thus determined, in part, by the linearity of frequency sweep in the Birnbaum refractometer and by the linearity of the discriminator response in the Crane form.

Levin *et al* [1982] sought to reduce the problems of restricted klystron linearity and multivibrator instability in the Birnbaum refractometer with a discrete frequency-scanning instrument. A highly-stable pulse generator was used to trigger a synthesized frequency generator programmed to step over the desired range in equally-spaced increments. The frequency difference measurement thus became a counting rather than a timing problem. Steps of approximately 25 kHz are apparently needed to yield an rms resolution of 1.0 N-unit. (Note, equation 3b indicates that a change of 1 N-unit would produce a change of 9.5 kHZ in the resonance of a nominal 9.5 GHz cavity).

Vetter and Thompson [1962] also sought to eliminate the difficulties associated with sweeping a klystron over a range of several MHz. In this case, an accurately calibrated tuning-probe was inserted in the end of the reference cavity. A servo system was then used to tune the reference to the resonant frequency of the sampling cavity. The probe position then became a direct measure of the ambient refractivity. The same approach had actually been used several years earlier by Sargent [1959], but this was apparently not recognized by Vetter and Thompson.

The most important advance in microwave refractivity was undoubtedly that described by Vetter and Thompson [1971]. These workers modified the Birnbaum refractometer by doing away with the reference cavity entirely. A voltage-controlled oscillator was tuned to a sub-multiple of the sampling cavity resonance by means of a phase sensitive detector. The VCO frequency was then counted after beating with a stable 100 MHz crystal oscillator.

The most recent development in refractometer design was outlined by Yilmaz *et al* [1983]. Apparently unaware of the Vetter and Thompson [1971] development more than a decade earlier, these workers also undertook a major simplification in refractometer design by completely eliminating the reference oscillator. More radical in its design, the Yilmaz version also shunned any stabilization techniques. Instead, they simply used a GaAs FET amplifier in series with the sampling cavity as a free-running oscillator. A microwave frequency counter was used to record the resonant frequency directly.

The simplicity of the Yilmaz design, however, should be approached with caution. In both the Vetter and Thompson [1971] and the Yilmaz *et al* [1983] refractometers, the frequency of an oscillator circuit is determined by the sampling cavity and the oscillator frequency is then measured. In this respect they each share an important characteristic of the Crane [1950] design. The Yilmaz version, however, shares one of the important characteristics of the Birnbaum form. In its original form, the Birnbaum refractometer placed more critical demands on the Qs of the two cavities than the Crane design. While the Crane version used phase-sensitive circuits to lock the oscillators to the cavity resonant frequencies, the Birnbaum refractometer made use of a variable-frequency swept oscillator to generate timing pulses. The measurement of these pulses was then subject to a jitter proportional to the resonant bandwidth; hence the extreme attention to cavity design.* By using an unstabilized oscillator circuit, the frequency of the Yilmaz refractometer would similarly

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* Note, Vetter and Thompson [1967] devised a special technique for locking onto the peak of the symmetrical cavity pulse, thereby reducing the intrinsic instability of the Birnbaum design somewhat.

be free to 'wander' in proportion to 1/Q. While it is difficult to estimate the magnitude of this instability under operational conditions, it would be unwise, in the author's opinion, not to lock the oscillator to the centre of the cavity resonance.

A further disadvantage of the Yilmaz design *vis à vis* the Vetter refractometer is that direct-reading microwave counters are both expensive and heavy. Use of a direct counter therefore restricts operation to an airplane or helicopter, whereas beating with a local oscillator is simple and could readily be incorporated in a telemetry system from virtually any platform.

4.2.3.2 *Temperature stability*

In measuring the tropospheric radio refractive index, one is interested in observing small-scale (spatial) fluctuations as well as the structure of moderately long (temporal) duration. Overall precision of the order of one part in 10^6 is indicated.

All of the expense and time involved in making tropospheric refractivity measurements would come to naught if instabilities or systematic errors of the type produced by temperature sensitive elements were allowed to go unchecked. Insofar as the electronic components and circuits are concerned the problem is not unduly complicated. In the case of the refractometer sensor itself, however, one comes face to face with limitations imposed by the properties of the materials being used.

In the very first published paper to discuss tropospheric microwave refractometers, Birnbaum [1950] pointed out that the expected fractional change in resonant frequency due to dimensional changes in the cavity is

$$\Delta f/f_o = -\alpha\,\Delta T \tag{4}$$

where α is the linear coefficient of expansion of the cavity material and ΔT is the causative temperative change of the cavity structure.

The best low-expansion metal available for cavity construction is invar, a high-density nickel-steel alloy. Depending critically on the precise metallurgical composition and treatment, invar generally exhibits a coefficient of expansion ranging from about 1×10^{-6}/deg C down to perhaps 5×10^{-7}/deg C. Bussey and Birnbaum [1953] and Lane [1965] used specially treated invar of select composition to achieve expansion coefficients of about 3×10^{-7}/deg C. Assuming a median value of 6×10^{-7}/deg C, a 10 degree change in cavity temperature would correspond to an indicated drift of $6N$ units in refractivity - greater than the changes of refractivity within some of the structures one would hope to examine.

As usual there are two or three basic approaches to the solution of this problem. The first approach is to attempt to construct a cavity in which the inherent temperature dependence is as small as possible. The second approach is to incorporate some form of temperature compensation into the basic design in order to reduce or eliminate nefarious thermal effects. The final approach is to defy the effects induced by changes in temperature and to apply corrections to the data, *a posteriori*.

Low-coefficient cavities

Considerable effort has been expended in trying to reduce the sensitivity of cavity resonators to changes in ambient temperature. In addition to invar, several other low-expansion materials have been examined. Thompson *et al* [1958] used a ceramic material to fabricate cavity barrels. Silver paste was fired onto the surface to provide the necessary conductivity. Cavity Qs (unloaded?) of 10,000-14,000 were reported. Final cavity temperature coefficients were approximately 1×10^{-7}/deg C – nearly an order of magnitude better than a typical invar resonator.

Gunderson and Smith [1968], working at Corning Glass, built an ultra-low expansion cavity, not surprisingly, out of a glass-ceramic material manufactured by Corning. The construction problems were so severe that screws of the same glass material were required for assembling the unit. The interior of the cavity was sprayed with a silver solution and fired, then polished to give an unloaded Q of 24,000, the highest ever reported for a refractometer cavity.

The material exhibited near zero expansion in the vicinity of 60°C. Indeed, between 50 and 80 degrees the cavity stability was a phenomenal 1.25×10^{-8}/deg C. At lower temperatures, however, the coefficient of expansion appears to tend asymptotically towards a value of $\alpha = -3 \times 10^{-7}$/deg C.

Chan and Cole [1978] likewise used vitreous materials to reduce thermal influences in their Crane-type refractometer. To that end, the sampling cavity was constructed of fused quartz, the reference cavity of low temperature-coefficient glass. The end walls were of brass for additional temperature compensation (discussed below).

In addition to the wide variety of refractometer designs discussed in this note, there are others of more novel form, probably destined to remain forever in limbo [*eg*, Thorn and Straiton, 1959; Kelly, 1975]. One design of great potential value, however, involved the use of spherical rather than cylindrical cavities [Cullen and Yu, 1972; Cullen *et al*, 1972; Matthews and Cole, 1974].

While the later instruments were not applied to tropospheric measurement, there is no overriding reason why they should not be so used, although additional development work would clearly be required. The use of two spherical mirror segments with an open space separating them produces a resonator with outstanding ventilation and apparently excellent Q. Matthews and Cole [1974] reported a thermal (frequency) coefficient of 5×10^{-7}/deg C using brass as the cavity material and claimed that 5×10^{-8}/deg C could be achieved if invar were used.

Temperature-compensated cavities

Complementary to the use of ultra low-expansion materials for cavity fabrication, Crain and Williams [1957] presented details of a straightforward method for compensating a closed cavity against thermal expansion by means of end plates of higher expansion-coefficient material such as brass or steel. The technique has been standard practice in the construction of sealed cavities ever since. Unfortunately, Thompson *et al* [1959] concluded that the technique was unsuitable for use on the open-ended sampling cavity. This point is a relatively important one. It is, after all, the sampling cavity which is exposed to the larger thermal fluctuations; the reference cavity – if one is used – can usually be maintained at a constant temperature. The author does not share the view that compensation of the sampling cavity is not possible. The difficulty in compensation likely arose from certain historical developments in refractometer design.

Most of the early studies of tropospheric refractivity were directed towards the detection of small-scale atmospheric turbulence. Because the true temporal and spatial resolution of a refractometer depends critically on the flow rate through the sampling cavity, a major goal during the decade of the 1950s was to increase the flowthrough without unduly sacrificing the circuit Q. The proportion of end surface area removed in the earliest refractometers was of the order of 35-45%, but this increased dramatically in the years that followed. The practical limit of 90% exposure was achieved by Thompson *et al* [1959] and this has more or less remained the accepted norm from that time on. At the same time, in order to maintain a high Q in so open a resonant structure, it was necessary to elongate the remaining annular portion into a short 'cutoff' waveguide section.

Attempts to compensate such a cavity in the same manner as the closed cavities gave rise to distortion of the fields within the cavity and this led to a drastic reduction in Q. It is the author's view that this is not a fundamental constraint and that a high degree of temperature compensation could be achieved with a slight compromise in end-plate exposure. Furthermore, such a compromise could be effected without degradation in refractometer performance for the application being considered here.

5. DEPLOYMENT TECHNIQUES

5.1 FIXED-BASE LOCATIONS

5.1.1 Tower, fixed instruments

The simplest of all possible systems, this approach has been used by Ikegami, Schiavone and others. The method is useful for observing mean vertical gradients and temporal variations. It is not a realistic technique for use in the 1980s in support of detailed propagation measurements.

5.1.2 Tower, winched instrumentation

Winching is potentially a very useful technique - provided a sufficiently tall tower is suitably located with respect to the propagation link and can be made available for this purpose. Since one would like to examine the atmosphere to altitudes of 300 metres or more, this option does not appear to be a very promising one.

5.2 QUASI-FIXED LOCATIONS

5.2.1 Kites

Kites are like children. Even under the best of conditions they exhibit a strong-willed obstinacy and reluctance to respond to well-intentioned guidance and control in the desired manner – at least in the hands of non-professionals. More importantly, the operational use of a kite would likely be limited to the interval between dawn and dusk and restricted to periods of modest wind conditions. Since anomalous tropospheric propagation is frequently at its worst during the pre-dawn period, and since wind shear appears to be implicated in the formation of certain refractive layers, these might prove an unacceptable set of restrictions.

5.2.2 Parachutes

Of necessity, the use of parachutes to lower an instrument package calls for another, complementary technology to lift and release the sondes. Each vertical profile measurement is transient, a second record requires the release of a second package. The advantages of a parachute descent are firstly, a more vertical profile than can be achieved with a propellor aircraft, secondly, passage through an atmosphere unperturbed by either aircraft or helicopter and thirdly, a continuous observation from the height of release down to ground level.

The use of parachute deployment would impose a number of special demands on instrument development. The packages would have to be constructed at minimal cost and in very large numbers since retrieval would not be possible or practical in the majority of cases.

5.2.3 Balloons

Of all the fixed-base techniques for tropospheric sounding, the balloon has and likely will continue to be the one most widely used. Its chief qualities are low cost, relatively simple technology, little dependence on outside cooperation (*cf.* towers, helicopters) and wide range of capability. Chan and Cole [1978] deployed a 1.5 kg expendable microwave refractometer for balloon soundings up to 2 hours in duration. Fowler *et al* [1966] actually lifted a three-cavity refractometer and associated electronics weighing 63 kg (140 lbs) to a height of 2.5 km by means of a tethered balloon of 128 m^3 (22 feet equivalent diameter)! Of course, balloons of this dimension are neither cheap nor simple to launch.

Crozier [1958] used a heavy fibreglass cable to restrain a variety of balloons, some of them quite large (over 28 m^3). Stainless steel cable, however, is probably the most weight-effective means of balloon restraint outside of modern fibre-composite materials. The weight of the cable effectively dictates the ultimate height attainable. Some workers have contemplated using cable triplets in a triangular arrangement in the hope of guiding the balloon along a more vertical track. Of course this method does not work reliably; one would require rigid, not flexible tethers for this purpose. Furthermore, the cable weight problem is tripled and the deployment problems are more than tripled. Slack produced in two of the three cables by strong winds can be awkward and is potentially dangerous.

The length of cable deployed can not be used as a reliable measure of payload altitude. An independent means of height determination is therefore necessary. Radar would be ideal but is probably unrealistic; triangulation by theodolite is possible but becomes complicated logistically and is restricted to periods of good visibility. A pressure sensor appears to offer the only real solution. To infer small height differences it would be necessary to have simultaneous temperature and water vapour profiles.

5.2.4 Kytoons

In principle, this hybrid device combines some of the best features of both the kite and balloon. An inflatable structure, it produces its own lift and is therefore independent of specific wind requirements. On the other hand, the lowered wind resistance presented by the prolate shape and the aerodynamic lift provided by the integral airfoil structure tend to eliminate the strong horizontal deflections due to wind that plague balloon flights. Venkiteshwaran *et al* [1982] used a 2m x 6m hydrogen-filled kytoon to lift a refractive-index-measuring package to a height of 400 m. The device was reportedly capable of lifting a 7.9 kg load off the ground. The weight of the package actually raised was not given.

5.3 RANDOM SAMPLING METHODS

5.3.1 Model airplanes

Remotely guided airplanes have long been suggested for use in probing the troposphere. Their advantages are extremely attractive; they thus warrant very careful and serious consideration:

(a) Model airplanes are relatively small and inexpensive. A large, 1/3-scale 'hobby' craft with approximately 3 metre wingspan might cost $400-500 in kit form, minus engine and controls; perhaps $1000-1200, fully equipped. Specially designed or larger models would, of course, be more costly depending on the degree of sophistication required.

(b) The model would be available for use at all times. Easily launched, the airplane could be operated without any outside assistance or services.

(c) Unlike a piloted aircraft, a model could be used to probe the lower few hundred metres of the troposphere right down to ground level.

(d) The device is highly manoeuvrable and relatively slow moving. It thus allows a fairly detailed examination to be made of atmospheric structures, both vertically and horizontally.

(e) Flight time is relatively short (under 1 hour) but refueling and launching are simple. In any event, continuous data recording is not required.

Of course, the model airplane, like each of the alternative options, carries with it a number of significant disadvantages or negative features:

(f) At least initially, the use of a model aircraft would be limited to the period between dawn and dusk. As is the case with a kite, flights would be restricted to periods of light wind.

(g) With a series of strategically positioned operators it is possible, in principle, to extend the operational range of a model aircraft to cover a complete radio hop. The problems inherent in such an effort are substantial ones. A number of flight-control operators would be required at locations along the entire length of the radio circuit, placing severe constraints on the selection of the test hop itself. In addition, accurate position determination over a distance of tens of kilometres would require a network of ground-based receivers and an on-board transponder. By contrast, operation over a range not exceeding one or two kilometres could be accomplished with a single radio control and two or three theodolites.

(h) The likelihood of a hard landing with damage to the aircraft and/or instrumentation is a distinct possibility. A minimum experimental program would call for two fully-operational models.

(j) Available airplane models appear to be capable of lifting 4-6 kg in addition to their engine, fuel and controls. Complete refractometer packages weighing less than 2 kg have been built; however, the load limit imposes an important constraint on instrument development.

(k) Unquestionably, one of the major problems standing in the way of using a model aircraft for tropospheric sounding involves the physical mounting of probes. The position of a pressure probe aboard the vehicle is not of paramount concern. To a slightly lesser extent the placement of a temperature element is not critical provided it is exposed to the air flowing past the airplane. Since the refractive index is strongly dependent on the relative humidity, however, the placement of a humidity sensor or refractometer is critically important. Either of these instruments would need to be positioned away from the skin of the aircraft in order to be very well ventilated. Furthermore, if small-scale structures such as refractivity gradient discontinuities or thin duct layers are to be observed then the sensors must be out of the wash of the propeller(s).

On a manned helicopter or small airplane these instruments may be positioned in front of or beneath the fuselage or on a wheel strut to avoid propeller turbulence. These are difficult positions on a model aircraft, especially if a refractometer is used. The only other location that is likely to prove acceptable is centrally mounted above the body and even this is problematic. A typical microwave refractometer cavity should weigh between 30 and 35 grams and present a cross-section of about 20 cm^2. The support structures and waveguide or cables would add to the drag. Raising the instruments above the wake from the nose of the model would produce undesirable top loading on the model. The impact of this on the airplane's stability and manœuvrability is unknown. A final evaluation of this problem is beyond the scope of this preliminary study and is likely outside the current expertise at CRC.

5.3.2 Manned aircraft

Both small and large aircraft are commonly used for studying the troposphere. While they lack the slow, precise altitude control and vertical tracking of instrument packages winched from a fixed tower, it is possible to fly a small craft in a reasonably tight spiral that approximates a vertical sounding. In any case, the very objective of a truly vertical profile is questionable.

The troposphere must vary horizontally; it is the rate, magnitude and quality of that variation that are generally unknown. Since radio wave propagation takes place over an extended area, modelling based on vertical profiles taken at a fixed location will inevitably be inaccurate. An airplane (or helicopter) can come closer to providing a comprehensive two- or three-dimensional representation of the the refractive index structure than any other method within reason.

The National Aeronautical Establishment (NAE) in Ottawa owns and operates a DeHavilland Twin Otter atmospheric research aircraft in cooperation with the Atmospheric Environment Service (AES) in Toronto. The aircraft is used as a research vehicle both for flight dynamics experiments and for cloud physics studies. In addition, the vehicle is available for use by other government departments during periods when it would otherwise be idle.

Although it is a much larger and more sophisticated aircraft than necessary for the study being considered here, it does have many excellent features. Because it is used exclusively as a research vehicle, the pilot/crew are well qualified to undertake the type of repetitive, low-level flight patterns desired.

The aircraft itself contains extensive on-board microprocessor and data recording facilities. The NAE instruments give a very accurate record of true atmospheric speed and position including the altitude above ground level. In addition, the instrumentation package provides output of both static and dynamic air pressure, static temperature and dew point temperature. It is quite possible therefore, that the NAE aircraft is already fully capable of providing all of the raw data needed for a preliminary experiment.

All of this is subject to limited availability, as mentioned. Flying time is normally booked well in advance for a number of special projects (acid rain, atmospheric polution, *etc*) in addition to its principal functions. When available, the aircraft is operated on a cost-recovery basis with the operating cost being approximately $500 per flying hour!

By contrast, unequipped ultra-small aircraft are available at a much more affordable price and on a more flexible time schedule. A Cessna model 172 with pilot rents for under $75 per hour. Suitable arrangements would have to be made regarding the physical mounting of instruments, probes, *etc*.

5.3.3 Helicopters

Helicopters have been used for radio propagation studies [Levin *et al*, 1978]; however, little reference is made to this mode of experimental study in the literature. It is likely that most of this work has been defence oriented and is therefore classified.

Virtually all of the arguments that can be made with respect to the use of small fixed-wing aircraft also apply to helicopters. In some important respects, they are superior vehicles for tropospheric research. Their lower air speed enables them to take a vertical profile in greater detail. They are also able to probe more safely down to ground level. At the same time, they are capable of sufficient speed horizontally to obtain nearly 'instantaneous' three-dimensional refractivity profiles.

On the negative side of the ledger, helicopter rentals are upwards of $450 per hour, operating out of Montreal, with a four hour per day minimum. In other words, the cost for a series of helicopter flights would equal or exceed the cost for using the NAE aircraft discussed above, but would lack all of that vehicle's sophisticated instrumentation.

6. CONCLUSIONS

One of the the main purposes of this report has been to present some of the highlights of a broad literature search and to present explicitly, in a semi-logical fashion, a wide variety of possible options for sober consideration.

As is evident from the report, numerous attempts have been made to probe the lower atmosphere in efforts to deal with the vagaries of terrestrial microwave propagation. Despite the diligence and abilities of those workers who, over several decades, have devoted themselves to this problem, it is nonetheless fair to say that no real advance has been made in our understanding of the intimate relationship between the refractive structure of the troposphere and anomalous radiopropagation characteristics or in relating these to broader geographic and/or synoptic weather conditions. An improved understanding of these relationships is essential if we are to proceed with useful propagation models or prediction techniques.

Technology and information processing have changed dramatically in the years since many of the experiments discussed in this report took place, offering renewed hope for success. Circuit miniaturization and improved component stability permit smaller, lighter probes to be constructed and launched. It is the author's view that the development and deployment of tropospheric refractive-index sounders is a legitimate activity within the Radio Propagation Laboratory and that such efforts would ultimately be of value to the scientific community and to the common carriers. Some definitive action should be taken at this time.

To be successful, a study of the variation in tropospheric refractive index must, as a minimum, be accompanied by supplementary measurements designed to detect multipath propagation conditions, either directly or indirectly. Ultimately, of course, all of these measurements and interpretations will need to be related to the performance of a digital radio link.

The emphasis throughout this report has been on the various aspects of meteorological instrumentation and measurement. The reasons are quite simple. Firstly, before any experimental program is undertaken the various meteorological methods and problems should be fully appreciated. Secondly, this may well be an opportune time to re-examine some alternatives in meteorological devices. While some show promise in terms of size or simplicity, only the microwave refractometer employing the standard cylindrical cavity has been thoroughly proven and accepted for the study of refractive layers in the troposphere. New, improved meteorological components may turn out to be better suited to tropospheric sounding in certain instances. The thorough testing and development necessary to establish confidence in any new device would best be carried out in a University environment. The author is of the view that such efforts within a suitable institution should be encouraged by CRC.

7. BIBLIOGRAPHY

An important component in the initial planning for any complex activity is the search and serious consideration of any work and/or knowledge which may already exist. The following bibliography represents a wide-ranging collection of published material of current and historical interest and related, in varying degrees, to the study of anomalous microwave propagation through the meteorology of the troposphere, especially its refractive index. The list is undoubtedly incomplete and includes material of varying merit; but since no such compilation was previously available, it is likely to prove useful for further research and study.

The references presented in this bibliography have all been extracted from unclassified sources: scientific and technical journals or from published conference proceedings. A few limited-distribution reports have been included for purposes of completeness. The following list of subject classifications has been applied to the reference material in order to provide some indication of content to the reader interested in a particular aspect of the subject under consideration.

0 =Review paper
1 =Propagation analysis
2 =Propagation models
3 =Radiometeorological analysis
4 =Experimental results and/or statistical analysis
5 =Theoretical analysis
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