VHF and Microwave Propagation Characteristics of Ducts

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Abstract— **Observations from many years of amateur radio operations together with commercial microwave propagation studies and are used to illustrate the nature of the VHF propagation in ducts. Recently developed formula for characterizing VHF and microwave propagation in ducts are used and modified to reconcile the observations with theory. Measurements from a high resolution SODAR are used to show the complex structure and characteristics of elevated ducts. The ducts are shown to have very strong temperature gradients and to form in substantially the same range over long periods. The ducts are very stable in the vertical plane and dissipate during the day. Equations are used to illustrate how propagation probably occurs in ducts and how signals enter and leave a duct. The nature of VHF propagation via ducts is illustrated using basic ray diagrams.**

I. INTRODUCTION

THE first direct association of beyond line-of-sight propagation of VHF signals with meteorological conditions was made by Ross Hull in 1934 [1]. Although Marconi had been able to send VHF signals beyond line-of-sight to a distance of 258km in 1933, he had not made the association with meteorological conditions although it was evident that such propagation could not be explained by diffraction [2,3]. Since Ross Hull published his work there have been many experiments conducted in many countries to measure the VHF and microwave propagation characteristics associated with various meteorological conditions including ducts. Work on the long distance propagation of short wavelength radar signals via ducts was greatly advanced during the Second World War and is published in [4]. Since 1950, many experiments have also been conducted on line-of-sight microwave telecommunications links by organizations such as Telstra, AT&T, British Telecom and Telia (Sweden) to determine how these links operate in the presence of ducts. The author has been involved in some of these microwave field experiments since 1982.

After about 1950, radio amateurs also began to conduct regular propagation experiments at VHF frequencies. An excellent review of some of this work is given by Howse [5].

From the short distance microwave propagation work conducted and extensive amateur observations it was evident to the author that many of the results could not be fully explained by the current theories of duct propagation and that a new approach was required. The development of some new concepts of VHF propagation via ducts reported here is an attempt to reconcile the observed results obtained from over 40 years of observations and measurements of VHF and microwave propagation in the lower atmosphere.

The amateur observations were started by the author in 1962 with observations on 144MHz along the Western Australian coast as VK6ZCN. From the late 70’s, the work was continued in Victoria on 50, 144, 432 and 1296 MHz as VK3YLR and later as VK3KAQ. This involved many VHF contacts to VK7, VK5, VK6 and ZL together with a great many observations from other amateurs such as those reported by Howse [5]. From the early 1980’s, the author worked at the Telecom Research Laboratories on microwave propagation and developing line-of-sight system design processes. Many papers were published about this work and several of the ideas developed in these papers were the direct result of observations of propagation behavior at amateur frequencies. The author is very grateful to the amateur community for making the amateur observations possible.

The new concepts of propagation via ducts that this paper is based on have been developed over several years [6,7] to overcome the inability of existing theory to explain the all observed effects, in particular the duct entry and exit effects.

Early duct propagation theory is based on geometric optics and is well summarised in [3]. This theory is unable to offer a complete explanation of all the observed duct propagation effects, in particular the widely observed frequency dependent effects. In his review of the mechanisms involved in duct propagation Howse [5] also found clear problems contained in the different concepts of the mechanisms involved in entry to and exit from a duct. The most recent work to develop techniques for analyzing propagation in ducts was published in 2004 by Isaakidis and Xenos [8]. This work used finite element methods to solve the parabolic equations used to describe propagation in a duct. It successfully describes the propagation in a surface duct but does not address the issue of propagation in elevated ducts or the problem of the radio wave entry or exit from a duct.

Some of the commonly held views about ducts that are considered by the author to be misleading and based on poor information or a misunderstanding of observed phenomena are:

- Elevated ducts can fall to become surface ducts.
- Surface ducts can rise to become elevated ducts.
- Ducts act as a wave-guide (from geometric optics theory of duct propagation).
- Ducts are frequency dependent.

- Coupling into the duct is only at the ends.
- The antennas must be in the duct.
- Evaporation ducts occur over land and sea.

There are of course many more ideas that could be added but do not pass even basic tests so these are left out. Because of the complexity of the propagation of radio waves via ducts, this work should be considered as a "work-in-progress".

II. FORMATION OF DUCTS IN AUSTRALIA

Howse [5] provides an excellent summary of the ducts that form in high-pressure systems and from sea breeze effects. By way of summary, some of the mechanisms that cause ducts to form are as follows:

- Subsidence (falling air) in high-pressure systems which causes a duct between about 400m and 800m to form over great distances along the costal regions of Western, Southern and Eastern Australia including the Tasman Sea in summer. In winter and spring, weaker ducts are evident in the costal regions at around 300m. Subsidence ducts can also form over large regions of inland Australia between 1000m and 1800m from autumn to spring.
- Sea breeze ducts form where the cooler sea breeze meets a warmer off land breeze. Sea breeze effects can also result in ducts at the top of escarpments such as along the Great Australian Bight near Eucla and along the Queensland coast. These ducts form where the warmer off land breeze meets a cooler sea breeze at the edge of an escarpment, such ducts have been observed by the author to cause extreme refractive gradients that affect microwave propagation.
- Surface ducts form where the ground cools by radiation forming a cool layer close to the ground with warmer air above it. Such ducts are usually less than 20m thick and are visible as a fog layer close to the ground. They form at night and break up after sunrise when heating of the ground reverses the process that formed the duct.
- Frontal ducts form where a wedge of cold air pushes under warm air to form a duct. These ducts may be several hundred km in length along the weather front and are locally short lived.
- Evaporative ducts form over water where the cooling near the surface from evaporation results in cool air below warm air and a temperature inversion.

III. VISUAL OBSERVATIONS OF DUCTS

Figure 1. 620m duct formed by subsidence in a high-pressure viewed from Mt Dandenong Victoria, 0Z 21 Dec 2002. close inspection shows the slight wavy top of the duct due to wind shear.

Ducts or temperature inversions are readily evident thorough the atmosphere from visual observation. An elevated duct at 600m is shown in Figure 1 and is the duct most often present in South Eastern Australia when long distance VHF propagation is observed towards the West in summer. Close inspection of Figure 1 reveals that the surface of the duct is wavy lending additional evidence to the concept of duct "roughness".

Propagation via the 600m duct can be stopped by high intervening terrain such as the Grampians in Western Victoria. Howse [5] comments on this terrain blocking effect noting that "the roughly East West valley between the end of the Great Dividing Range and the Otway Ranges may preserve the far end of the duct". In autumn and spring, high-pressure systems often sit over the mainland and have ducts at around 1400m, such ducts enabling contacts between NSW and SA. Elevated ducts become weaker in the daytime and re-establish in the early evening.

Radiosonde data is taken a various locations around Australia every 12 hours and is relatively course but can be used to estimate the position of elevated ducts such as shown in Figures 1 and 5. Although the radiosonde flight times are not always optimum from a propagation point of view they provide a valuable indication of the long distance duct propagation conditions.

Figure 2. Surface duct formed due to radiation cooling over land, 6am local time.

A surface duct formed by cooling of the air close to the ground is shown in Figure 2. Surface ducts are generally between 3m and 5m high. Signals can be trapped by the surface duct and propagate along the ground until the duct dissipates or until a blocking object is encountered such as a line of trees or a hill. Signals can also be refracted from the top of a surface duct. Surface ducts break up after sunrise from heating of the ground and rise to dissipate between 50m and 300m above ground.

Figure 3. Evaporative duct over water where the distant shore line appears to be extended vertically.

An evaporative duct is shown in Figure 3. Signals can propagate along the surface of the water in an evaporative duct. These ducts can be present for days at a time. Evaporative ducts can act as an RF mirror (and sometimes an optical mirror) and reflect signals from the top of the duct.

Ducts can be easily located by visual observation especially if the observation is close to the height of the duct as shown in Figures 1, 2 and 3.

IV. OBSERVED CHARACTERISTICS

The data used to draw conclusions about the characteristics of ducts was obtained from three different observation methods:

- A large number of amateur radio contacts by the author in Western Australia and Victoria on the bands from 50MHz to 1296Mhz plus the observations of many other amateurs. This work and the work of McAllister and Baker in conducting long term measurements between Albany and Sailsbury is discussed by Howse [5].
- Professional work by the author on design and optimisation methods for fixed microwave radio links in the commercial bands below 10GHz operating over distances of 30km to 165km.
- An acoustic pulse compression SOund Detection And Ranging (SODAR) system for obtaining high resolution vertical profiles of the atmosphere up to 2km recently developed by the author.

The amateur radio observations led to numerous effects being observed during long distance propagation via ducts, most of these are listed below:

- Propagation distances of over 2000km have been observed on all amateur bands from 144MHz to 10GHz.
- Ducts vary in their ability to transport signals, weak ducts may only propagate up to 144Mhz while strong ducts may sometimes propagate 10GHz signals.
- As ducts become stronger and transport higher frequencies the lower frequencies seem to become weaker.
- Stations often report being “passed over” by the duct, stations either side of them can work via the duct, but they hear nothing.
- Ducts can terminate abruptly with stations only 30km further on hearing little or nothing.
- Ducts form in the evening and break up in the late morning but sometimes remain through the day although weaker than at night.
- Excellent ducts are present in Southern Australia from about December to March and over inland Australia from about March to October. Exceptions to these times are often noted.

The professional observations lead to several other effects being observed on microwave paths of 30km to 165km:

- Extreme elevated ducts at a given location are always close to the same height at a given time of the year.
- The elevated ducts form in the late evening, are strongest around 6am local time and break up in the late morning.
- Elevated ducts interact with microwave signals by refraction through the duct and/or propagation along the duct.
- The surface ducts can be extreme and form a highly microwave reflective layer close to the ground.
- Surface ducts can propagate signals along the ground until they reach an obstruction.
- Surface ducts break up due to heating of the ground after sunrise.

- Very strong ducts occur in Southern Australia in summer and in the more Northern parts of Australia in Winter.
- The *k-factor* fading or sub-refraction [9,10] does not happen at all except in or very close to a duct. The *k-factor* of the gross atmosphere is 4/3 at all times. All of the effects attributed to k-factor fading can be more correctly explained by the effects of surface ducts [11].

V. SODAR MEASUREMENTS

A pulse-compression SODAR measurement of the lower atmosphere to a height of 1100m ASL for a period of 7 days during a ducting event is shown in Figure 4.

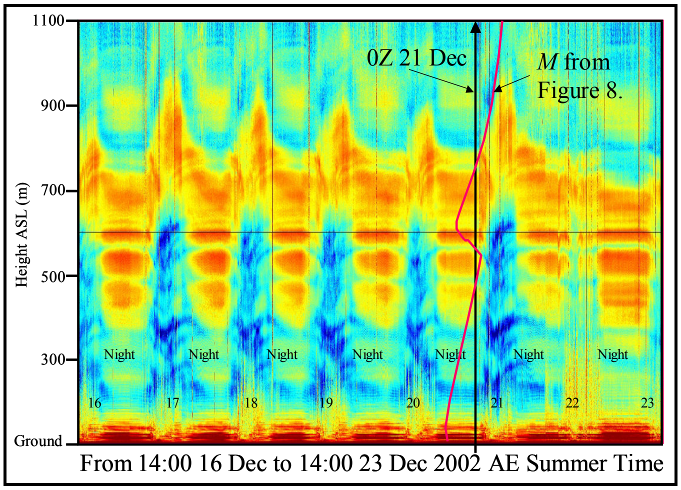

Figure 4. SODAR observations to a height of 1100m ASL over seven days. Red areas are highest signal return and blue areas are lowest signal return. A strong elevated duct is evident at 600m for 7 nights where the amplitude of the return SODAR signal is highest. The corresponding *M* profile from Figure 8 for 0Z on 21 Dec 2002 is also shown. The calculated *M* profile corresponds well with the highest SODAR signal level. The elevated duct clearly forms during the night and breaks up during the day due to the effects of rising plumes from ground heating. Ground level is at 100m. 3895 measurements with 2m vertical resolution.

The measurements shown in Figures 4 and 5 are of the return signal level that is indicative of the vertical refractivity. Ducts are clearly indicated by the highest signal levels in red. Blue areas represent low refractivity and low humidity from low signal levels. The highest signal levels correspond well with the calculated *M* profile from a radiosonde measurement.

The position of the elevated duct at close to 600m does not change at night over a period of 7 days. During this time, several high-pressure systems passed with central pressures from 1019 hPa to 1030 hPa indicating that the position of the 600m elevated duct does not change with the evolution of the high-pressure systems.

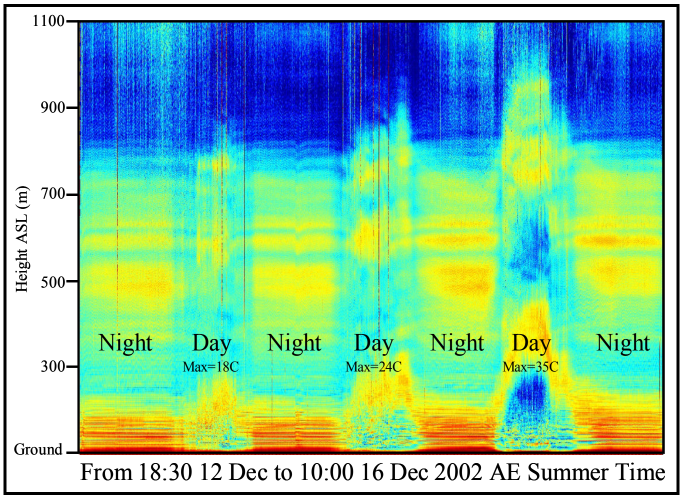

Figure 5. SODAR observations to a height of 1100m over three days. A ground based temperature inversion is evident during the night to a height of 200m ASL (100m above ground). During the day, the plumes of rising warmer air break up the ground inversion. The daytime maximum temperatures are shown, higher maximums cause the ground inversion to be driven higher. A weak duct is evident at around 600m. Blue areas represent lower humidity. 1400 measurements with 2m vertical resolution.

Several SODAR returns are averaged in Figure 6 to show the estimated virtual temperature structure. This gives a more detailed look at the structure of ducts and shows that the vertical structure is very complex. It also shows that very high temperature gradients are possible within a duct creating highly refractive layers.

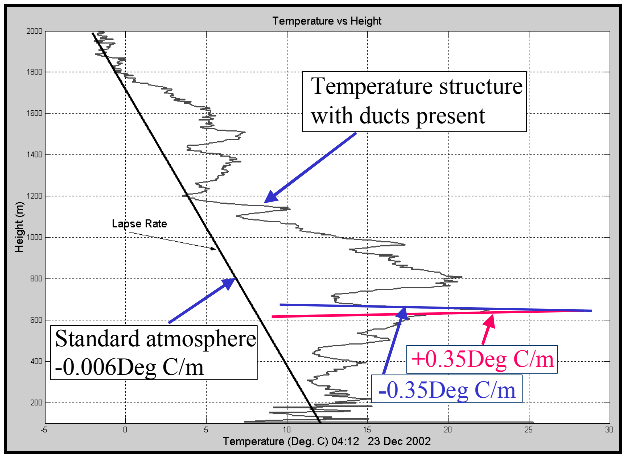

Figure 6. Vertical virtual temperature measurement with a duct present and the "normal" temperature lapse rate of –0.006 Degrees C/m shown as a solid line. This result is calculated from several SODAR return signal level results and illustrates the increase in temperature with height up to 800m with several dramatic variations along the way. Maximum temperature gradient is close to 0.35 Degrees C/m with temperature changes of 7 degrees over just 20m. Ground based ducts are also present.

The SODAR system also provides very high resolution measurements of wind. Several wind profiles through an elevated duct are shown in Figure 7. This data clearly shows the change in wind direction associated with an elevated duct. This change in wind direction or wind shear causes the surface of the duct to be rough in a similar way that wind over water can roughen the water surface.

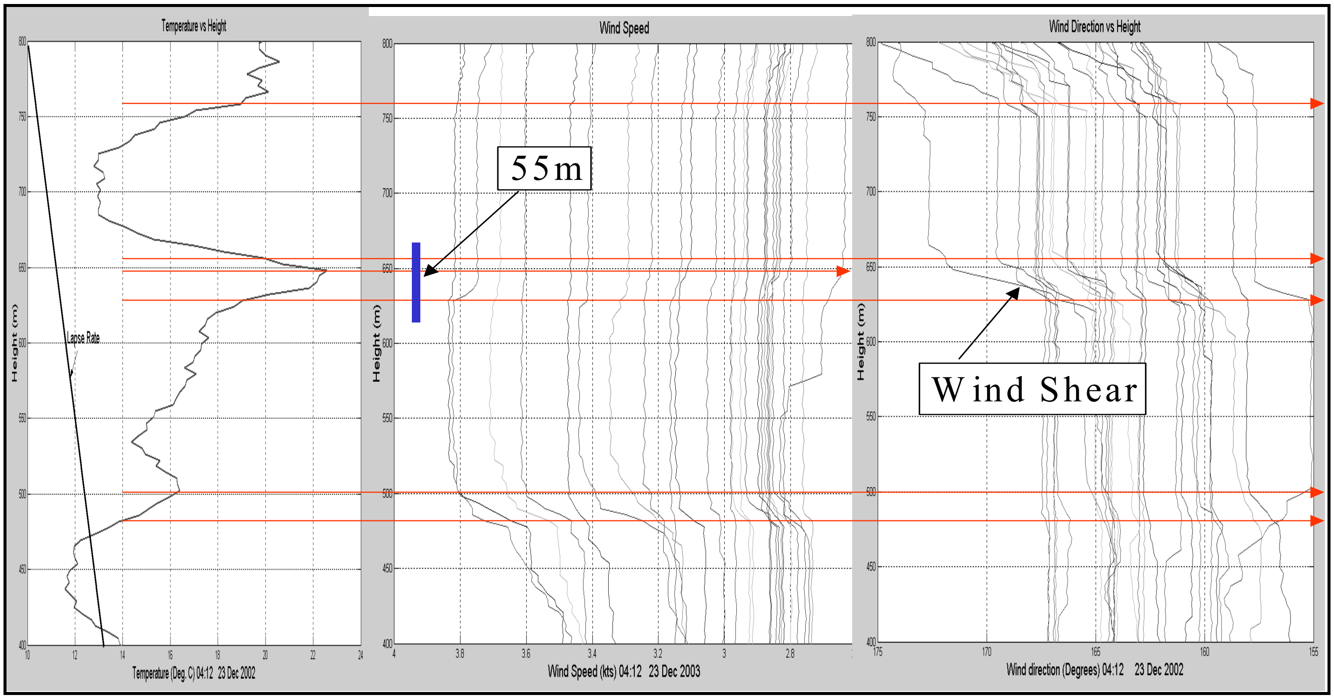

Figure 7. SODAR observation of the vertical structure of an elevated duct showing detail including wind speed and direction. There are two ducts evident, a weak one between 480m and 500m and a strong on between 630m and 685m. Changes in wind speed and direction are directly associated with the ducts.

The SODAR measurements were conducted over the summer 2002-3 from which the following observations were made:

- Elevated ducts form at a given height and break up at that height.
- Strong ducts are present in the night and if present during the day are much weaker.
- Vertical duct structure is very complex and is not well represented by low resolution radiosonde measurements.
- An elevated duct can have several structures present in it, ducts within ducts.
- Several duct structures can be present at the same time including elevated ducts and ground ducts.
- Ground ducts do rise during the day but not sufficiently to result in long distance propagation. They become much weaker due to the effects of rising plumes of air breaking up their structure.
- Wind shear is present across the surface of an elevated duct.

From the SODAR observations shown in Figures 4, 5, 6 and 7, several of the misunderstandings set out above can be readily dismissed. In particular;

- *Elevated ducts can fall to become surface ducts:* This is specifically not the case for ducts above about 300m, there are no observations that support this. Elevated ducts remain elevated, they form and break up at a given height.
- *Surface ducts can rise to become elevated ducts:* There are no observations to support this. Ground ducts do rise after sunrise and then break up from thermal plumes that disrupt the duct during the day.

I. OBSERVATION AND THEORY

Ducts occur in meteorological conditions where the temperature increases with increasing height over a distance of a few 10's of meters, instead of decreasing with increasing height as is normal in a well mixed atmosphere. Regions where the temperature increases with height are called temperature inversions. An example of an elevated temperature inversion is shown in Figure 8 where at around 580m the temperature increases over a short distance from about 18 deg. C to about 24 deg. C at 680m. Above and below this point the temperature is seen to decrease with height in the normal way.

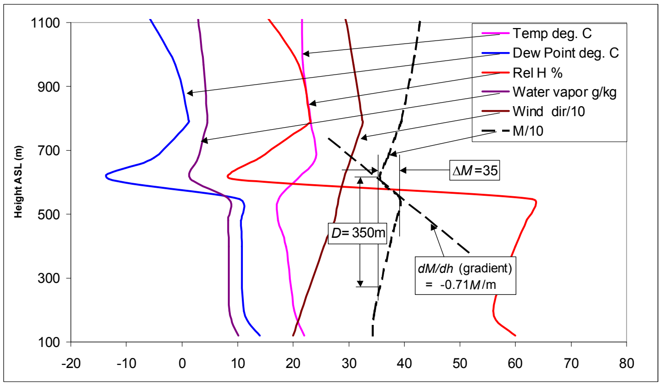

Figure 8. Radiosonde temperature, dew point, humidity, water vapor content, wind direction (divided by 10) and calculated M profile (divided by 10) showing an elevated duct at 600m due to subsidence in a high-pressure system, Melbourne 0Z 21 Dec 2002, from [12]. The depth of the duct is 350m, the gradient of the *M* profile in the duct is –0.71*M*/m and the maximum M difference is 35*M* units.

Such temperature inversions trap water vapor below them to form a duct as shown in Figure 8 where at around 580m the water content decreases from about 8gm/kg below the temperature inversion to 3gm/kg above the inversion. A corresponding dramatic decrease in humidity that is associated with the temperature inversion is also evident in Figure 8.

From amateur observations the two most outstanding effects of ducts are that the upper and lower frequency limits are well defined and have something to do with duct strength while closer to a duct is better for achieving long distance contacts. These effects will be used to validate the equations that describe duct behavior. Several other observed effects are noted later.

The most common way to calculate a duct profile is to obtain the modified refractive index *M* [13] from:

$$M = \frac{77.6}{T}\left(P + \frac{4807 * e}{T}\right) + 0.157 * h \qquad (1)$$

where:

T is temperature in degrees Kelvin
P in the pressure in hectopascals
h is the altitude in meters
and e is the vapor pressure given from:

$$e = 6.1078 * 10^{\{7.5 * T_d / (237.3 + T_d)\}} \qquad (2)$$

where T_d is dew point temperature.

A series of duct *M* profiles is shown in Figure 9 where the differences in the different types of ducts are evident.

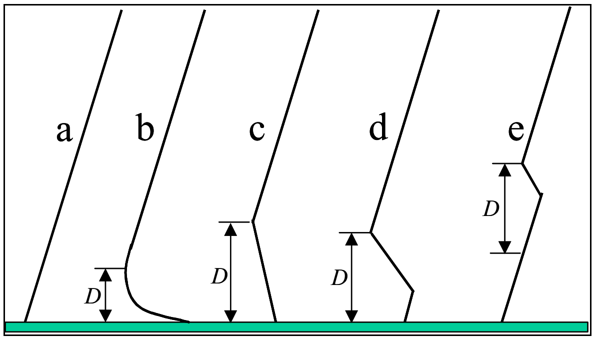

Figure 9. M profiles for various types of ducts showing a standard atmosphere (a), evaporative duct (b), surface ducts (c and d) and an elevated duct (e). The depth of the duct *D* is shown for each type of duct.

The data to calculate the *M* profiles can easily be obtained [12]. Using equations (1) and (2) an *M* profile for the data of Figure 8 is calculated and shown in Figure 8. This *M* profile indicates the presence of an elevated duct at 600m (see Figures 8 and 9). The elevated duct position in Figure 8 corresponds to the increase in temperature and a decrease in humidity and further corresponds to the increase in signal amplitude from the SODAR measurements of Figure 4 taken at the same time. A change in wind direction is also associated with the duct, the wind shear also being seen in the SODAR data of Figure 7. The water vapor content decreases above the duct indicating that water vapor is trapped by the temperature inversion.

The elevated duct has a depth of 350m, a width of 35 M units and a duct gradient *dM/dh* of 0.71*M*/m, Figure 1. Typical values for duct gradients are between 0.1 (weak gradient) and 2 (strong gradient). The ***size*** of the duct (depth and width) determines the minimum frequency, equation (3) while the ***strength*** of the duct (gradient and depth) determines the entry and exit angles for the duct, equation (4).

Having set out the basic properties of a duct, the propagation characteristics can now be investigated. An estimate of the longest wavelength that can be propagated by a duct using the duct dimensions can be estimated from [14]:

$$\lambda_{\min} = 0.66 * A * D * \sqrt{\Delta M} \qquad (3)$$

where:

A is $3.77 * 10^{-3}$ for a surface duct and $5.66 * 10^{-3}$ for an elevated duct
D is the depth of the duct in meters
ΔM is the maximum difference in the modified refractive index within the duct.

The maximum wavelength that can be transported for a range of measured ducts and is shown in Figure 10 [14]. This concept of a maximum wavelength (minimum frequency) that a duct will support is consistent with all of the amateur observations. For the data from Figure 8 and using Figure 10, the minimum frequency that could be transported by this duct is about 60MHz (5m) as it is quite a large duct. As the depth of the duct becomes shallower, shorter maximum wavelengths are supported as shown in Figure 10.

The amateur observations show there is also a maximum frequency that a duct can support. This is further confirmed by the work of Baker and quoted by Howse [5]. This is an issue because the current theory does not indicate that a duct has a maximum frequency as well as a minimum frequency.

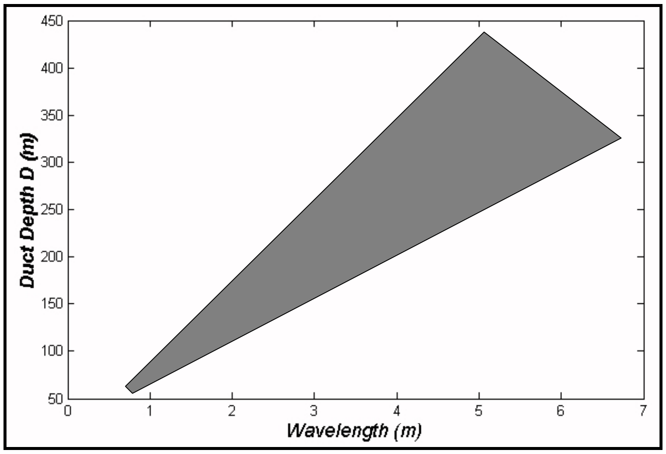

Figure 10. The range of maximum wavelengths that could be transported by a duct of particular depths calculated from measured data.

It may be that in fact the entry into and exit from the duct is frequency dependent and provides an explanation for the observed effects. A formula from [15] gives the critical angle Φ_t at which a signal can be trapped by a duct:

$$\Phi_t = 7.39 * 10^{-2} * \sqrt{(|dM/dh|) * D} \quad \text{deg.} \qquad (4)$$

where:

$|dM/dh|$ is the magnitude of gradient of modified refractive index.

The duct parameters of Figure 8 give a trapping angle of 1.16 degrees. Equation (4) assumes that the refractive index gradient is linear over the whole duct and that the surface of the duct is smooth. As (4) is not frequency dependent, it indicates that all frequencies above f_{min} would be trapped by the duct. It is most likely that (4) is very conservative and that the duct structure is more complex resulting in a gradual low and high frequency cut off rather than one well defined low frequency boundary suggested by (4). The observations show that trapping by a duct has a lower *and* upper frequency limit. There is thus a need to arrive at a better understanding of the mechanisms involved.

By modifying equation (4) to include a frequency dependent ratio, a formula that better describes the trapping by a duct as a function of frequency and duct parameters is obtained that is now more consistent with the observations. The concept of this modification of (4) is that the duct trapping angle is reduced by the ratio of the duct minimum frequency to the operating frequency. This formula can be used to estimate the maximum trapping angle Φ_{tf} for any given frequency to enter into a duct. For duct trapping angles greater than Φ_{tf} the given frequency will not be trapped by the duct and will pass through. This addition of a frequency dependent ratio to (4) now provides the observed frequency dependence so that:

$$\Phi_{tf} = \Phi_t * f_{\min} / f \text{ deg.} \quad (5)$$

where:

f is the frequency for which the angle of trapping to the duct is required and $f > f_{min}$ so that $\Phi_{tf} < \Phi_t$.

Equation (5) effectively forces a band-pass frequency dependent term onto equation (4) to describe the observed behavior, the modification being based on intuition. The duct entry angles given by Equation (5) over a range of duct depths and f_{min}/f and for dM/dh =1.0 are shown in Figure 11.

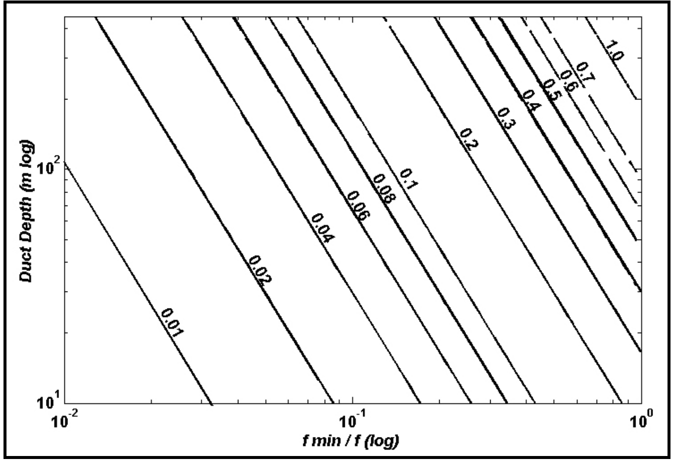

Figure 11. Duct entry angle (degrees) for a range of duct depths and f_{min}/f with dM/dh = 1.0. For other values of dM/dh multiply the above angles by sqrt(dM/dh). The data assumes that the duct is smooth. For a rough duct with 4km wavelengths and a height variation of +-2m the minimum sustainable duct entry angle is about 0.1 degrees. The duct roughness has the effect of providing an upper frequency limit for a given duct strength.

To illustrate the effect of the combination of minimum wavelength and actual frequency consider that a strong duct with a 150m depth has an approximate maximum wavelength from Figure 10 of 2m (144MHz). The corresponding duct trapping angle at 144MHz from Figure 11 is around 0.8 degrees for a duct dM/dh of 1.0. For an operating frequency of 1.2GHz (9 times or f_{min}/f of 0.11) the duct trapping angle is now about 0.1 degrees. This indicates that a station operating at 1.2 GHz has to be considerably closer to the duct than a station operating at 144MHz in order to minimise the duct trapping loss. For a larger duct of 320m depth and with the same dM/dh of 1.0, the maximum trapping wavelength is about 5m or 60MHz with a duct maximum entry angle of over 1 degree. The 1296 MHz station with f_{min}/f of 0.046 has a duct trapping angle of 0.06 degrees and needs to be close to or in the duct otherwise the duct trapping loss will be too high preventing communication at 1296.

The wind shear across the duct surface shown in Figure 7 causes the surface of the duct to be rough. This surface roughness distorts the duct surface by giving it a wave shape that is just visible in Figure 1. This surface wave now causes the duct to have a continuously changing angle with respect to the horizontal so that a signal propagating along the duct is now required to adapt to this shear induced roughness angle. If the angle of trapping to the duct at a particular frequency is smaller than the shear roughness angle then the signal will not be trapped by the duct. The shear roughness angle Φ_{SR} is approximated by:

$$\Phi_{SR} = a\sin(4 * A_S / \lambda_S) \text{ degrees} \qquad (6)$$

where:

A_S is the amplitude of the surface roughness and

λ_S is the shear wavelength.

For a duct with a λ_S of 4km and an A_S of 2m the shear roughness angle is 0.1 degrees. For the previous example of a 1296MHz signal with a trapping angle of 0.06 degrees, a shear roughness angle of 0.1 degrees would indicate that the 1296MHz signal would not be able to be trapped by the duct. At 10GHz it is even more critical to be in the duct or very close to it of duct propagation is to be contemplated.

It is thus evident that higher frequencies will have higher duct trapping loss than lower frequencies accounting in part for the observed frequency dependence assuming that the duct is smooth and follows a nice curve. If the surface of the duct is rough due to the effects of wind shear then the trapping angle will be need to be larger for any given frequency. This effect will further reduce the upper frequency limit that the duct can transport.

The equations above plus the assumption that ducts have rough surfaces gives a reasonable explanation of the observed frequency dependence for ducts with different strengths and also provides an explanation of the various duct entry and exit effects noted.

II. 20 DECEMBER 2002 ANALYSIS

On 20 December 2002 good propagation conditions were reported between Esperance and Melbourne [16]. The MSL analysis map for this day shows a large high-pressure system with a central pressure of 1021 positioned in the Great Australian Bight, Figure 12. This is a classic “good VHF propagation” situation [5].

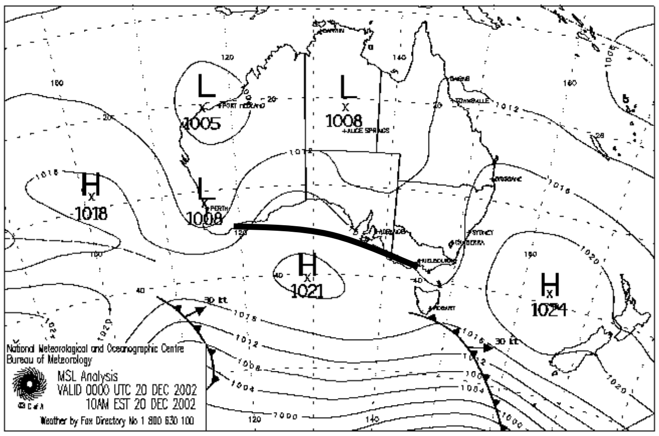

Figure 12. MSL analysis for a period of good VHF propagation from Esperance to Melbourne on 20 December 2002.

To find out a little more about the nature of the duct that was present on 20th December the radiosonde soundings from Albany, Esperance, Eucla, Adelaide, Mt Gambier and Melbourne are analysed to provide *M* profiles for each of the stations and are shown in Figure 13. The *M* profiles show an elevated duct at Albany, Esperance, Eucla and Mt Gambier. The top of the elevated duct is at a height of between 600m and 700m on the Western end of the path and at 500m at Mt Gambier. There is evidence of a duct at Melbourne as the *M* profile is bent above 500m. The time of the profile at 11:00 am local time means that there was probably sufficient surface heating to break up the duct structure on this day. The SODAR data from Figure 4 provides clear evidence for a duct being present earlier in the day on 20 December 2002 at 600m. It is interesting to note that the top of the elevated duct in this high-pressure system is entirely between 500m and 700m providing further evidence that the height of the duct is similar over the whole high-pressure system. There is no evidence of the elevated duct drooping down to become a surface duct, see Figures 4, 5 and 13.

The profiles from the western end of the path are taken at 09:00 local time when the duct has not yet been disturbed by local heating. The profile from Adelaide shows no evidence of an elevated duct and may have been disturbed by local surface heating as the temperature was 30 Degrees C at the time of the observation. The path taken by the VHF signals from Esperance to Melbourne passes South of Adelaide so that if a duct is not present at Adelaide it does not have any effect on this path.

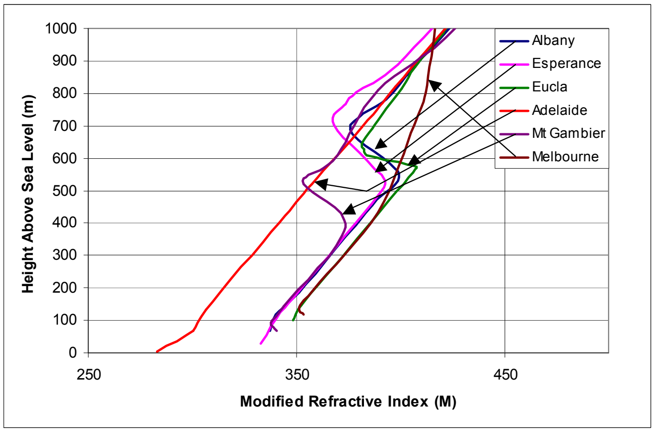

Figure 13. *M* profiles for the indicated stations for 00:00 UTC, 20 December 2002. This indicates the position of the elevated layer around the time of the good propagation conditions.

The wind direction for the same time of the M profiles is shown in Figure 14. The wind is approximately East on the Western part of the path and goes more Southerly further towards the Eastern end of the path. Above about 500m the wind goes more Northerly at the Western end of the path and more Southerly at the Eastern end of the path resulting in the wind shear associated with the elevated duct. These wind directions are entirely consistent with wind in a high-pressure system where the surface wind flow is in an anti-clockwise around the high-pressure system. It is this wind direction and the presence of elevated ducts that indicates that the high-pressure system causes the elevated ducts and that most likely no other meteorological effect is involved in the formation of elevated ducts. This discounts the requirement of sea breeze effects to form a duct over this path [5].

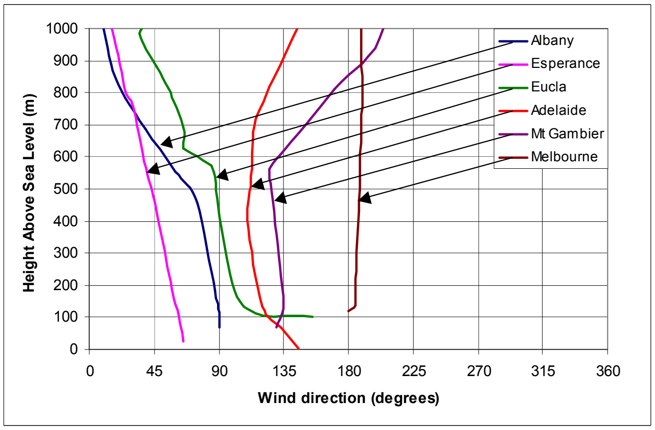

Figure 14. Wind direction for the indicated stations for 00:00 UTC, 20 December 2002.

III. PUTTING IT ALL TOGETHER

In order to understand how the observed effects and the theory come together the structure of the duct needs to be examined in some detail. The elevated ducts are of the most interest for long distance propagation and are discussed here.

The elevated duct structure is very complex. It has substantial temperature changes and associated changes in wind speed and direction (wind shear) Figures 4, 5, 6 and 7.

This wind shear shown in Figure 7 is caused by the subsidence in high-pressure systems when the falling drier air encounters the cooler, denser more humid air below and results in a "balance point" and resulting wind shear. At this "balance point" the compression of the falling air causes an increase in temperature as the falling air is compressed against the more dense air below. The changes in temperature and humidity plots are readily evident in Figures 4, 5, 6, 7 and 8 at around 600m. When the temperature increases with a corresponding decrease in humidity a duct is formed.

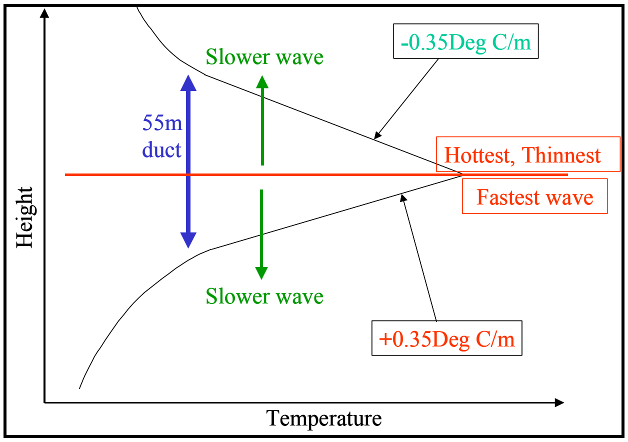

Figure 15. In the duct the upper and lower boundaries have a temperature gradient of 0.35 Degrees C/m. At the hottest part of the duct the air is driest and thinnest and radio waves travel faster than in the cooler parts of the duct where the radio waves travel slower.

The mechanism by which radio waves are refracted in a duct is that the wave front travels faster in the less dense air found at the center of the duct and slower in the cooler, more dense air further from the center of the duct. The radio signal is thus refracted away from the center of the duct as shown in Figures 15 and 16.

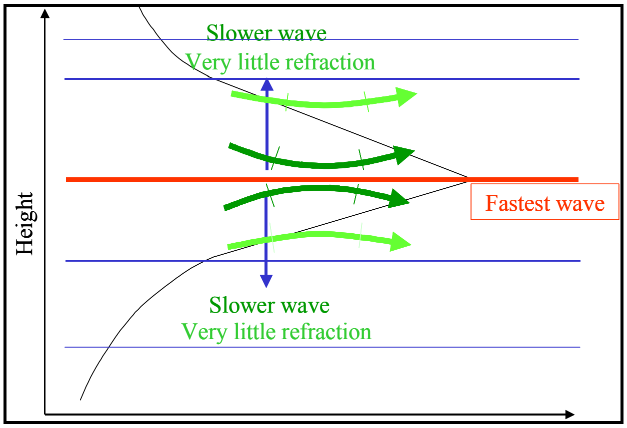

Figure 16. At the center of the duct the wave front is bent more than further out in the duct resulting in a bending of the wave front.

If the radio wave comes from above the duct, assuming that the duct is smooth, it can be refracted out again and not stay in the duct at all and sub-refraction occurs, Figure 16. If the radio wave is able to maintain exactly the right position and stay within the duct the wave is able to travel great distances by super-refraction, Figure 17. This is difficult to achieve as the duct will probably not have exactly the right refractivity gradient to achieve this.

It is more likely that when the radio wave enters the duct it will repeatedly enter and leave the duct by refraction along the lower side of the duct and by this means travel great distances. This concept of repeated refraction is able to explain long distance propagation via ducts with the variable refractivity gradients that are more evident in practice. The angles of refraction are of course very small as each refraction may be up to 50km apart, Figure 18.

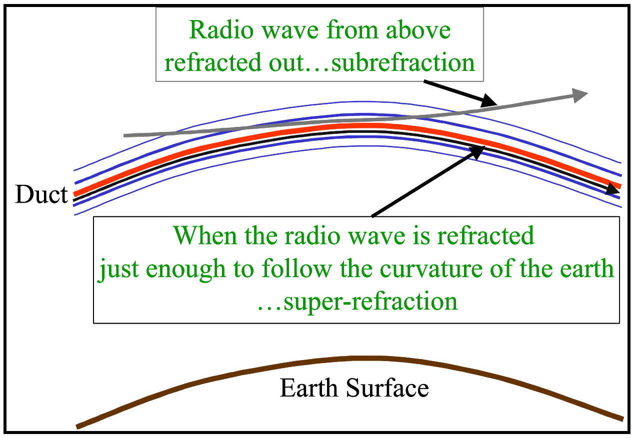

Figure 17. When the radio wave is refracted from above the duct the wave can be refracted out of the duct in a process known as sub-refraction. When the radio wave is in the duct it can be refracted just enough to stay within the duct so that supper-refraction occurs and the radio wave travels over great distances if the temperature gradient is optimum. Slight changes in the temperature gradient would prevent the signal from maintaining its position in the duct.

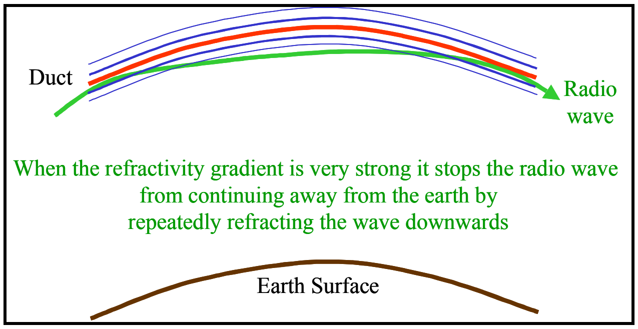

Figure 18. The radio wave does not stay exactly in the duct but is repeatedly refracted out only to re-enter at greater distances. This process more easily describes the observations and the ability of the duct to propagate many different frequencies depending on the duct temperature gradient.

As the trapping angle of the signal to the duct increases the radio wave is less likely to be refracted enough to stay in the duct and it will reach the point where it will pass through the duct, Figure 19.

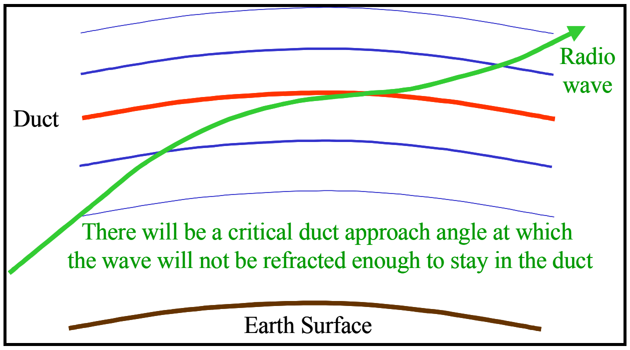

Figure 19. If the angle of the signal to the duct is larger than the duct trapping angle the signal passes through. This is a frequency dependent effect.

So far only a smooth duct has been discussed. Wind shear associated with the formation of the duct, Figures 7 and 8, causes the surface of the duct to be rough in a manner that the surface of the ocean is roughened by the wind across its surface. This roughness can readily be seen on the top of elevated ducts, it has a wavelength of about 4km (not electromagnetic wavelength but wind wavelength) and is evident from close inspection of Figure 1.

This roughness provides a lower limit to the duct trapping angle so that higher frequencies with smaller duct trapping angles cannot be propagated via the duct. For instance, a duct roughness length of 4km and a variation of the duct vertical position of +-2m results in a duct roughness angle of about 0.1 degrees. This means that frequencies which require duct entry angles of less that 0.1 degrees cannot be sustained in the duct because the duct roughness causes them to "spill out". This provides an upper limit to the frequencies that a particular duct can propagate. The only way that higher frequencies can be propagated via a duct is for the duct depth to decrease, for the duct gradient to increase and/or the duct roughness to decrease. This provides a reasonable explanation as to why weak ducts cannot propagate microwave signals and why frequencies of up to 10GHz are only rarely propagated over long distances via a duct because the very strong ducts required occur only rarely.

This roughness allows signals to enter and leave the duct more easily so that the duct is "leaky" along its entire length, Figure 20. As the turbulence scatters the radio signal, there will be an associated loss of the signal because of the multiple refractions from the turbulent duct surface.

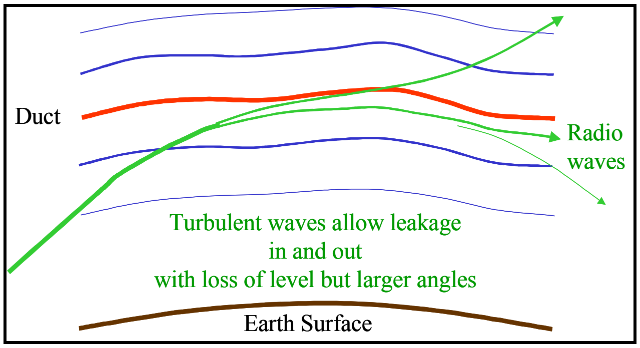

Figure 20. Due to wind shear the duct surface is not smooth but rough allowing signals to enter and leave more easily, also resulting in an upper frequency limit for the duct.

The entry angle to the duct is a critical factor and is a reason why stations at higher elevations are able to use the duct over greater distances than stations at lower altitudes. As the ducts become more extreme the refractive gradients are higher and the entry and exit angles are consequently smaller. This is the reason that under some very good conditions stations towards the middle of the path where refractive gradients are higher, can be "passed over" and miss out on the DX altogether.

The concepts developed here are able to explain all of the effects noted earlier and provide a better understanding of the characteristics of elevated ducts and how VHF and microwave signals interact with them.

To return to the issues:

- *Ducts act as a wave-guide:* This is a very misleading concept and probably incorrect. The signals travel along the duct by multiple refraction from the surface roughness of the duct. The duct acts as a "boundary layer" by guiding the signals around the surface of the earth by multiple refraction from rough surfaces.
- *Duct is frequency dependent:* The lower frequency limit is related to the duct strength and depth while the upper frequency limit is set by the duct roughness.
- *Coupling into the duct is only at the ends:* This may appear to be the case but coupling towards the middle of the duct depends on the strength of the duct and the entry angle so for some stations well below the duct it may appear as if the coupling is only at the ends.
- *The antenna must be in the duct:* It is not essential to be "in the duct" but clearly closer to the duct is better and is illustrated by the higher placed stations working more DX via ducts.
- *Evaporation ducts occur over land and sea:* Evaporative ducts only occur over water, radiation cooling is the cause of ground ducts over land unless of course a lake is present in which case an evaporate duct also occurs.

IV. SUMMARY

From the results of many observations and the development of a better understanding of the characteristics of elevated ducts the following results and observations can be summarized:

- Elevated ducts remain elevated, they form and break up at a given height, the height of the 600m elevated duct does not change with the evolution of the high-pressure systems.
- Surface ducts rise and break up during the day and fall in the evening to reform near the surface, they do not rise to sufficient height or remain strong enough to propagate VHF/UHF signals over long distances.
- The radiosonde is not very accurate for predicting ducts, it is limited in resolution and often misses key structures, but is excellent when there is nothing else.
- Ducts act more like a boundary layer by repeatedly refracting VHF and UHF signals resulting in long distance propagation.
- The smaller the entry angle (closer) to the duct the better the coupling.

- Characterizing the duct as a "wave guide" is probably incorrect given the evidence.
- The duct is frequency dependent, band pass, the low frequency cut-off being determined by the duct depth and strength while the high frequency cut-off determined by the roughness.
- Surface evaporation ducts occur over water, surface radiation ducts occur over land.
- Stations at higher elevations are able to work more duct related DX than stations at lower elevations because of the reduced entry angle into the duct with higher elevations resulting in better signal levels from distant stations.
- High-pressure systems in the Great Australian Bight are probably the only mechanism required for elevated ducts to form, there are no other mechanisms required.
- The duct in a high-pressure system is at approximately the same height over the whole high-pressure system.

ACKNOWLEDGMENT

Tele-IP Limited is acknowledged for providing data from its StratoSonde SODAR for use in this paper [17]. The many contributions from other amateurs by way of observations and just being there to make a contact are also acknowledged. The publication of an earlier version of this work in Amateur Radio Magazine [18, 19, 20] is also acknowledged. The helpful comments of the reviewers Don Graham (VK6HK) and Wally Howse (VK6KZ) are also acknowledged.

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