VHF and Microwave Propagation Characteristics of Ducts

Andrew L. Martin, VK3KAQ

***Abstract*— Measurements from many years of amateur radio observations together with commercial microwave propagation studies and are used to illustrate the nature of the VHF propagation. It is shown that much of the commonly held understanding of ducts and VHF and microwave propagation in the lower atmosphere is poor. Measurements from a high resolution SODAR are used to show the 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. The nature of VHF propagation via ducts is illustrated with basic ray tracing and estimations of the signal-to-noise ratios at different frequencies for two different station locations using recently developed concepts for signal entry into a duct and propagation along a duct.**

I. Introduction

THE work reported here is the result of over 40 years of observations and measurements of VHF and microwave propagation in the lower atmosphere. This work was started in 1962 with observations of 144 and 432 MHz 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. From the early 1980's I 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. I am very grateful to the amateur community for making these observations possible.

Some of the commonly held views about ducts that I consider 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.
- The radiosonde is accurate for predicting ducts.
- Ducts act as a wave-guide.
- Duct is frequency dependent.
- Coupling into the duct is only at the ends.
- Your antenna 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. The rest of the paper is arranged to present many of the observations and to draw some conclusions from these observations to develop some new concepts of how radio signals might interact with ducts.

II. Observations of Ducts

Ducts or temperature inversions are evident in many forms thorough the atmosphere due to the large number of mechanisms that form ducts.

Figure 1. 620m duct formed by subsidence in a high pressure viewed from Mt Dandenong Victoria, 0Z 21 Dec 2002.

Ducts or regions where the temperature increases with increasing height over a distance of a few 10's of meters, instead of decreasing with increasing height, are also called temperature inversions. 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 very large distances along the costal regions of Western, Southern and Eastern Australia including the Tasman Sea in summer (Figures 1, 2 and 3). In winter and spring weak ducts are evident at around 300m. Subsidence ducts can also form over large regions of Australia at between 1000m and 1800m, these ducts are generally not evident in summer.
- Sea breeze ducts form where the cooler sea breeze meets a warmer off land breeze at the top of an escarpment such as along the Great Australian Bight near Eucla and along the Queensland coast. These ducts form at the level of the escarpment.

- 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 (Figure 4). They form at night and break up in the early morning.
- Evaporative ducts form over water where the cooling near the surface from evaporation results in cool air below warm air and a temperature inversion (Figure 5).

Several other mechanisms can also cause ducts to form such as along fronts but are of less interest to radio amateurs.

Ducts are characterized by changes in the vertical radio refractive index gradient such as shown in Figure 3. This refractive index gradient was obtained using data from a radiosonde flight [1] (Figure 2.) and a program called AREPS [2].

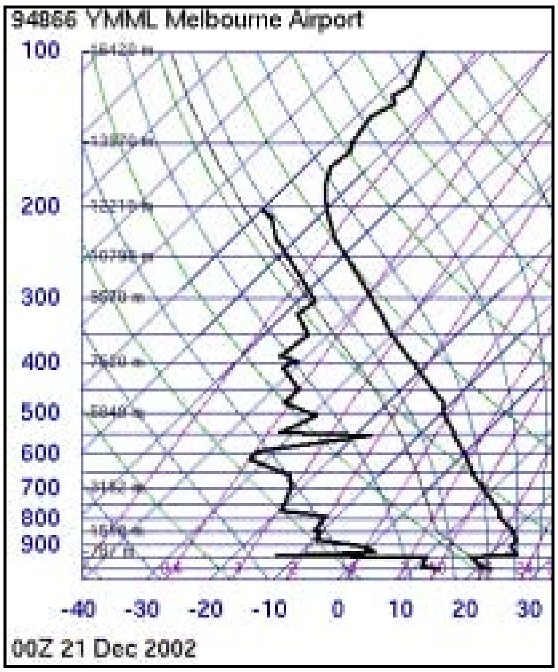

Figure 2. Radiosonde temperature and humidity data showing an elevated duct at 600m due to subsidence in a high pressure system, 0Z 21 Dec 2002.

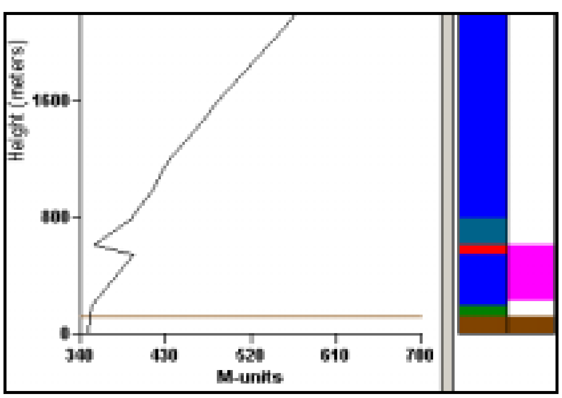

Figure 3. Reverse refractive index gradient indicating the presence of an elevated duct, 0Z 21 Dec 2002 (from AREPS, [2]).

Figure 4. Surface duct formed due to radiation cooling over land, 6am local time.

Surface ducts are generally between 3mand 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 reflected 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 200m above ground.

Figure 5. Evaporative duct over water where the distant shore line appears to be extended vertically.

Signals can also 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, 4 and 5.

III. Observation Tools

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 in Western Australia and Victoria on the bands from

50MHz to 1296Mhz plus the observations of many other amateurs.
- Professional work on design and optimisation methods for fixed microwave radio links in the commercial bands below 10GHz operating over distances of 30km to 165km.
- A recently developed acoustic pulse compression SOund Detection And Ranging (SODAR) system for obtaining vertical profiles of the atmosphere up to 2km.

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 50MHz 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 be “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 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:

- The 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 and propagation along the duct.
- The surface ducts can be extreme and form a highly 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 so called k-factor fading or sub-refraction[3][4] does not happen at all and except in or very close to a duct. The *k-factor* of the gross atmosphere is 4/3 at all times.

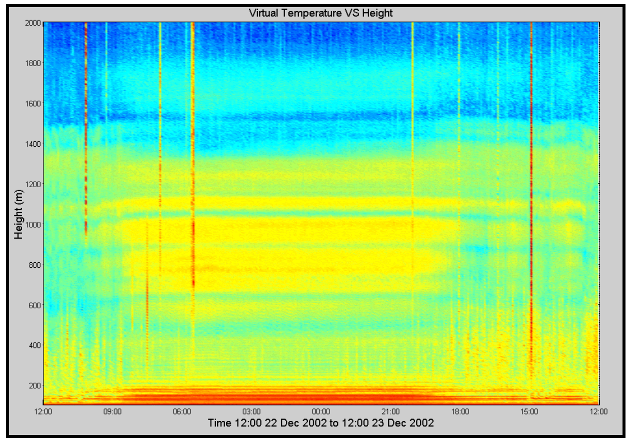

Figure 6. SODAR observation to a height of 2000m for one day. Strong elevated ducts are evident at 620m and 1050m (darker areas) during the night and break up during the day. Weaker ducts are also evident at 500m, 900m and 1500m. Rising plumes of warm air are evident up to 18:00 and start again after 09:00 and break up the ducts. Strong vertical lines are noise, time axis is from right to left. Ground level is at 100m. 360 measurements, 4m vertical resolution.

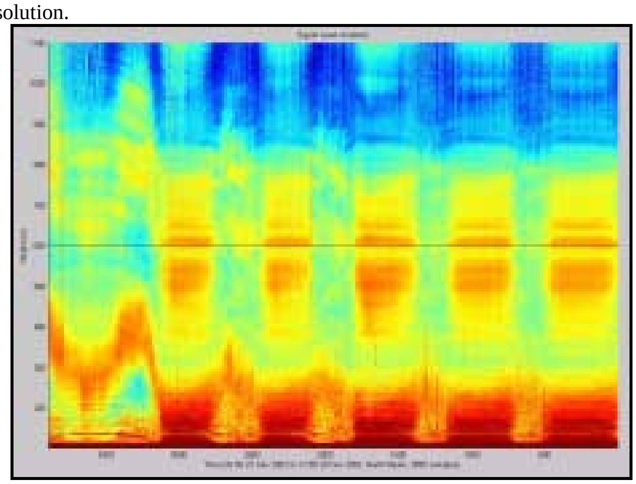

Figure 7. Vertical structure for 6 days to a height of 1100m measured by SODAR. Time is right to left. Elevated ducts are evident around 600m during the night for the first 5 nights, in the last night the high pressure system has moved away and the day time temperatures increase so that ducts can no longer form. Strong vertical plumes are evident in the day. There is no evidence of ducts rising to become elevated or elevated ducts falling to become ground ducts. The surface inversion layer at around 280m breaks up during the day. On the last 1.5 days the surface inversion layer rises due to the effect of ground heating. 3895 measurements with 2m vertical resolution, ground level is at 100m.

The observations from a pulse compression SODAR are shown in Figures 6, 7, 8 and 9. The measurements are of the return signal level that is indicative of the vertical refractivity. The 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.
- The vertical temperature gradients in a duct are very high causing extreme ducts to be formed.
- Vertical structure is very complex and is not well represented by low resolution radiosonde measurements.

- 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 as they become much weaker due to the effects of ground heating.

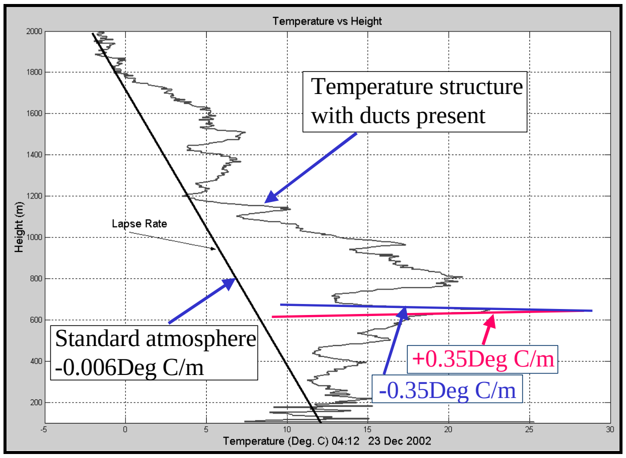

Figure 8. Vertical temperature measurement with a duct present and the "normal" temperature lapse rate of –0.006 Degrees C/m shown as a solid line. This result is calculated from several SODAR return signal level results and illustrates the increase in temperature with height up to 800m with several 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.

From the observations shown in Figures 6, 7, 8 and 9, several of the misunderstandings set out above can be readily dismissed. In particular;

1) *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.
2) *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.
3) *The radiosonde is accurate for predicting ducts:* The radiosonde is not very accurate and often misses key structures because of a lack of vertical resolution.

IV. A Close Look at an Elevated Duct

In order to understand how the observed effects listed earlier come about the structure of the duct needs to be examined. The elevated ducts will be discussed as those are of the most interest in long distance propagation.

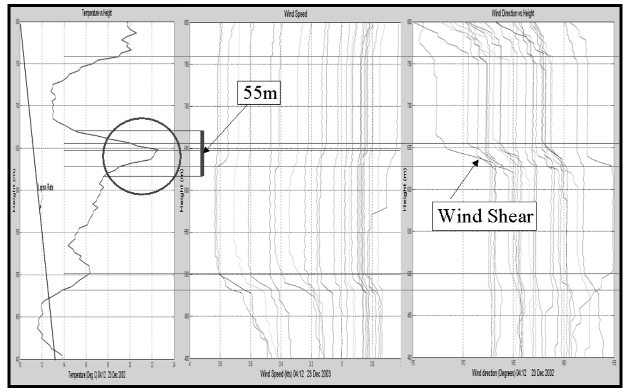

Figure 9. SODAR observation of the vertical structure of an elevated duct showing detail including wind speed and direction. There are two ducts evident, a weak one between 480m and 500m and a strong on between 630m and 685m. Changes in wind speed and direction are directly associated with the ducts.

The elevated duct structure is very complex and besides having substantial temperature changes, changes in wind speed and direction (wind shear) are also associated with elevated ducts. This wind shear is caused by the subsidence in the high pressure system 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 results in a temperature increase as the falling air is compressed against the more dense air below. The temperature and humidity plots are readily evident in Figure 2 at around 600m, when the temperature increases, the humidity decreases and a duct is formed.

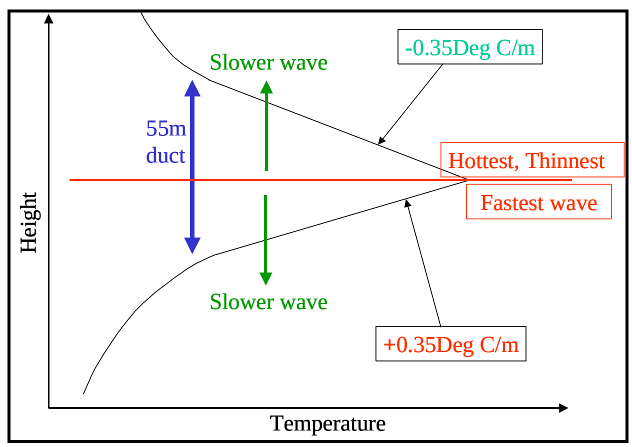

Figure 10. In the duct the upper and lower boundaries have a temperature gradient of 0.35 Degrees C/m. At the hottest part of the duct the air is driest and thinnest and radio waves travel faster than in the cooler parts of the duct where the radio waves travel slower.

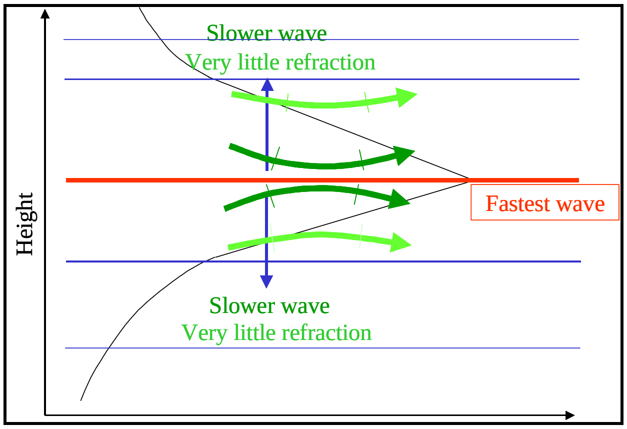

Figure 11. At the center of the duct the wave front is bent more than further out in the duct resulting in a bending of the wave front.

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 and consequently 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 10 and 11.

If the radio wave comes from above the duct it can be refracted out again and not stay in the duct at all and sub-refraction occurs (Figure 12). 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.

This is difficult to achieve and it is more likely that if the radio wave enters from below the duct it will repeatedly enter and leave the duct by refraction and by this means travel great distances. The angles of refraction are of course very small and each refraction may be up to 50km apart (Figure 13).

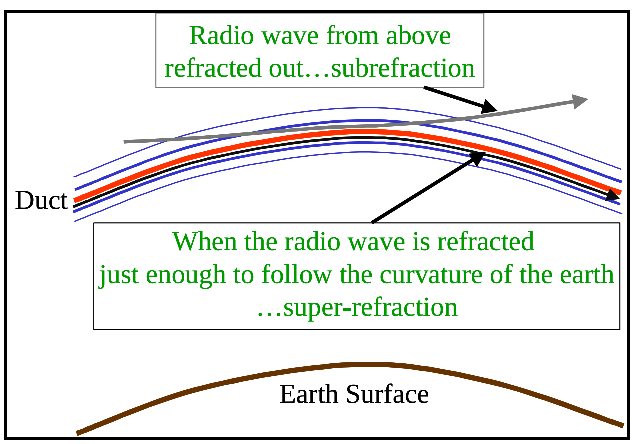

Figure 12. When the radio wave is refracted from above the duct the wave can be refracted out of the duct in a process known as sub-refraction. When the radio wave is in the duct it can be refracted just enough to stay within the duct so that supper-refraction occurs and the radio wave travels over great distances.

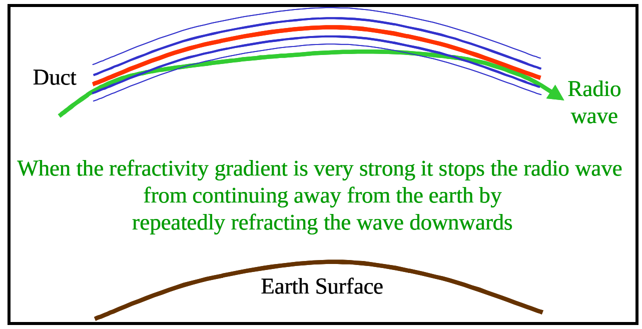

Figure 13. The radio wave does not stay exactly in the duct but is repeatedly refracted out only to re-enter at greater distances.

As the angle of entry into 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 14).

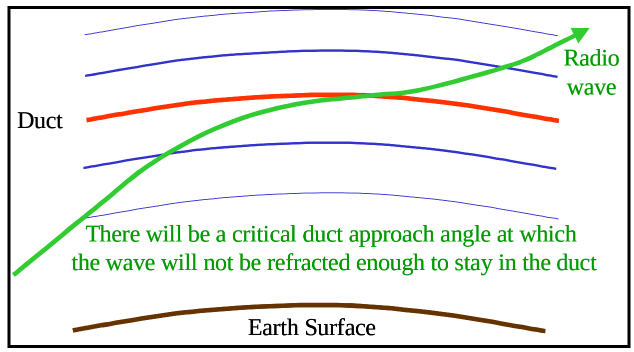

Figure 14. When a critical angle is reached the radio wave coming from below the duct passes through.

So far only a smooth duct has been discussed. Wind shear associated with the formation of the duct 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 allows signals to enter and leave the duct more easily so that the duct is "leaky" along its entire length (Figure 15).

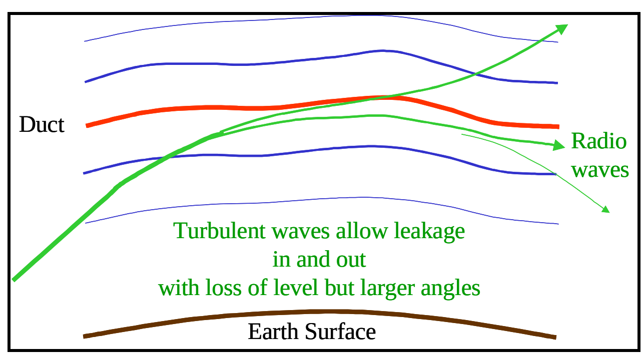

Figure 15. Due to wind shear the duct surface is not smooth but rough allowing signals to enter and leave more easily and at greater angles.

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.

To return to the issues, the next one stated from the introduction is;

4) 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. It is more like the duct acts as a “boundary layer” by guiding the signals around the surface of the earth by multiple refraction as shown in Figure 13.

V. The Bigger Picture of the Elevated Duct

So far we have looked at the localized effects of the duct. This section is to have a look at the bigger picture to see how ducts can appear to have frequency dependence. From Figures 14 and 15 it is evident that the entry angle into the duct is crucial parameter when considering how signals are “captured” by the duct, weaker ducts can accept higher entry angles than stronger ducts. In other words, the angle at which signals can enter the duct is inversely proportional to the refractive gradient of the duct. The duct structure does not go on forever so that at the ends of the duct it becomes weaker and the refractive index gradient is also smaller. This means that the acceptable entry angles into the duct are larger at the ends of the duct than in the middle for a given station height (Figure 16). The result of this effect is that stations at the end of the duct can partake of the DX while stations in the middle of the duct have difficulty even hearing distant stations. This is because the useable angle of entry is much smaller in the middle of the duct because of the higher temperature gradient there. Stations closer to the duct (higher) seem to have more luck than stations at lower altitudes.

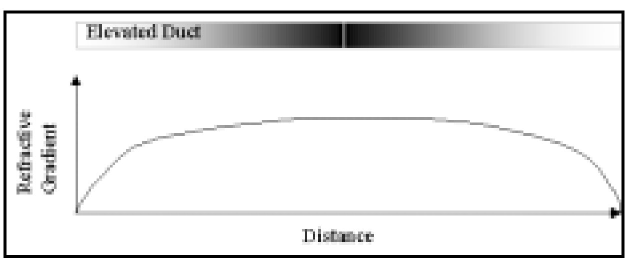

Figure 16. Elevated ducts can extend over great distances but do come to an end. At the ends the refractive index gradient is lower than in the middle implying that the entry angle at the ends of the duct is larger at the ends than in the middle.

From the results obtained over the years it is evident that there is a great deal of variation of the DX capabilities of different stations when using ducts at VHF. To explain this a new view of the attenuation to enter a duct has been developed (Figure 17) in order to explain the observed effects.

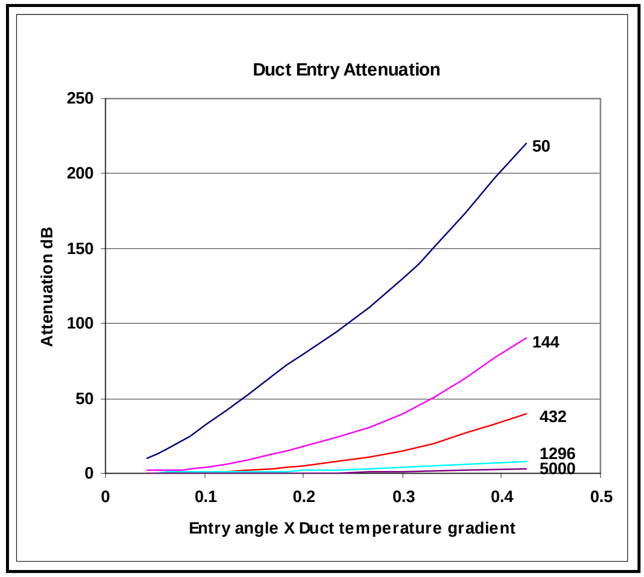

Figure 17. Estimated attenuation at various frequencies to enter the duct as a function of duct temperature gradient (duct gradient or strength) multiplied by the duct entry angle in degrees. The duct entry attenuation also applies to a signal leaving the duct.

When there is a weak duct with a very small temperature gradient (in degrees C/m) the duct entry attenuation is also very small. As the duct strength increases with increasing temperature gradients, for a given entry angle it becomes more difficult for lower frequencies to enter the duct so that as the duct gets stronger lower frequencies are more attenuated on entry to the duct that higher frequencies. Similarly, for a constant duct strength, as the entry angle is reduced the attenuation to enter the duct is reduced so that stations that are closer to the duct have less entry attenuation (Figure 17). If a station is well below a very strong duct, lower frequencies are greatly attenuated so that the signal may not be received at all and the signals can sometimes seem to “pass over” a particular station. In such cases going to higher frequencies may provide better results.

The distance that a station is from the duct sets the angle of entry to the duct. For a station at 100m and a duct at 600m, the entry angle is approximately 0.8 degrees at a distance of approximately 40km (Figure 18).

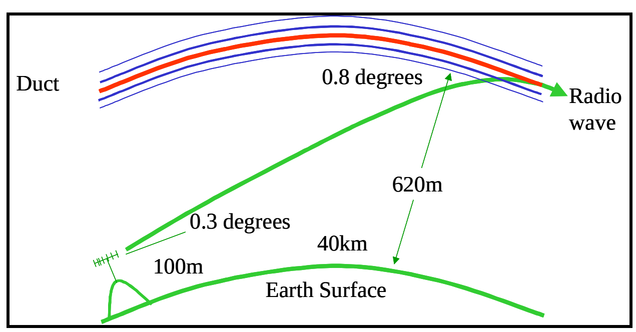

Figure 18. Duct entry angle for a station at 100m and a duct at 620m.

To obtain the abscissa value for use in Figure 15 multiply the duct temperature gradient by the duct entry angle. A very strong duct has a temperature gradient of 0.35 degrees C/m.

A further effect that is observed is that weak ducts are more able to propagate lower frequencies, (Figure19). This effect is in addition to the effect of entry into the duct noted previously.

Even if stations are well situated it does not mean that higher frequencies can be used, the general pattern is that as the duct strengthens higher frequencies improve. Compared to stations at lower altitudes, higher altitude stations can of course use higher frequencies because of the reduced entry angle loss at higher frequencies. By combining the effects of the two graphs it is evident that entry angle and duct strength combine in a complex fashion resulting in some apparently odd effects.

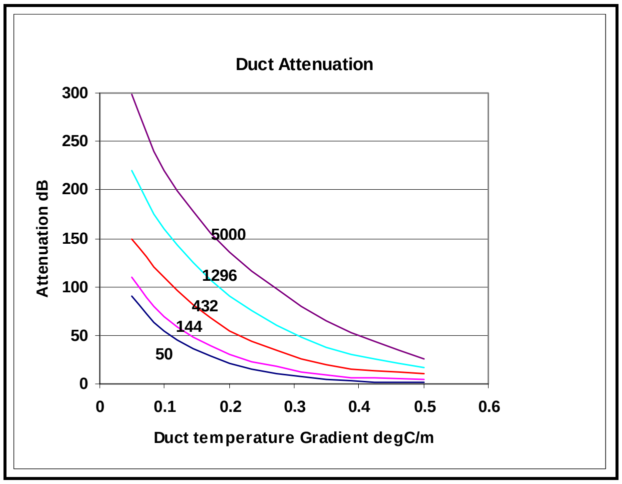

Figure 19. Estimated attenuation in the duct as a function of duct temperature gradient. Attenuation is normalised to the attenuation at 50MHz. As the duct becomes stronger it is able to propagate signals with lower attenuation but high frequencies are more attenuated than lower frequencies.

Freq	Power	Antenna	Rx bandwidth	Feed loss
50	100	9 dBd	2 kHz	4dB
144	100	12 dBd	2 kHz	4dB
432	50	14 dBd	2 kHz	4dB
1296	10	15 dBd	2 kHz	4dB
5000	1	20 dBd	2 kHz	4dB

Figure 20. Station parameters for estimating the signal-to-noise ratio for propagation via an elevated duct. Receiver noise figure is 3dB for all bands.

In order to estimate the signal-to-noise ratio of signals propagated via a duct a set of station parameters was selected (Figure 20). From these parameters and the distance over which the signal-to-noise ratio is to be estimated, the free space signal-to-noise is first calculated. A handy program for this is available in the VK3UM Software Suite from [5]. Once the free space signal-to-noise is calculated the signal-to-noise ratio at the required distance can be estimated for a given duct strength from:

S/N=Free Space S/N - Entry and Exit Attenuation – Duct Attenuation (dB). 1.

This formula is now applied to two cases of station location for propagation via a duct over 2500km. The results are shown in Figures 21 and 22.

By looking at just the 50MHz case it appears that unless a station is in or very close to the duct then the entry level attenuation alone will prevent any signals from being heard by stations below the duct. At 144 MHz there is less entry attenuation but the duct propagation attenuation is higher. This effect continues on through the higher frequencies.

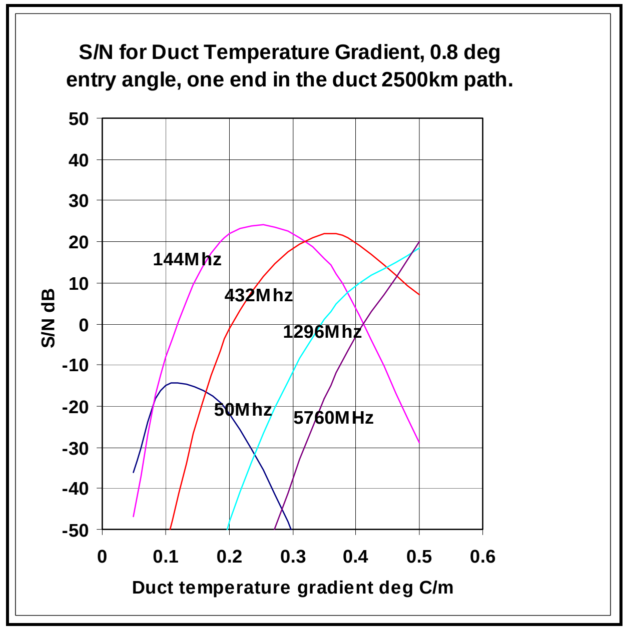

Figure 21. Estimated signal-to-noise ratio for the station parameters of Figure 20, the duct entry attenuation of Figure 17 and duct attenuation of Figure 19, calculated using formula 1. One station is assumed to be in the duct at 620m and the other station is below the duct at 100m.

For the case of extreme ducts, stations at microwave frequencies can gain entry to the duct even though they may be several hundred meters below it and explains much of the success from using microwave frequencies.

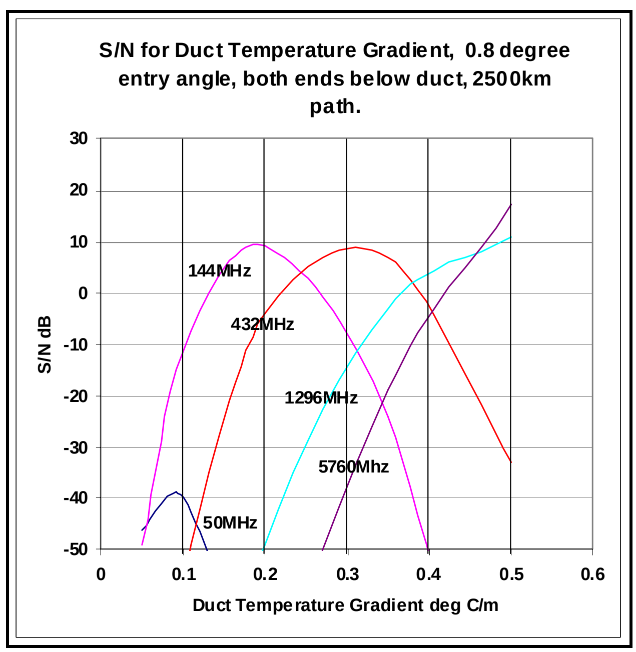

Figure 22. Estimated signal-to-noise ratio for the station parameters of Figure 18, the duct entry attenuation of Figure 15, duct attenuation of Figure 17, calculated using the formula 1. Both stations are at 100m and the duct is at 620m.

The attenuation at microwave frequencies in an extreme duct is much lower than in weaker ducts so that long distance contacts are occasionally made at microwave frequencies when ducts are strong enough. The data of Figure 21 shows that as a duct gets stronger the signal-to-noise ratio improves at higher frequencies while lower frequencies drop off illustrating one of the most reported effects of duct propagation. In Figure 22 the signal-to-noise ratio is calculated for a 2500km path where both stations are at 100m. By comparing Figures 21 and 22 it is evident that for the same duct strength the signal-to-noise ratio is reduced when both stations are below the duct, again illustrating another often noted effect that the closer to a duct a station is the better the signals. The signal-to-noise ratio for shorter distances than 2500km can be easily estimated by increasing the signal-to-noise ratio by 6dB for every halving of the path length. For a 625km path and the same station parameters just add 12dB to the signal-to-noise values given in Figures 21 and 22.

Another effect evident in Figures 21 and 22 is that propagation at 50MHz is possible but the signal-to-noise ratio is very poor making communication via ducts at this frequency very unlikely. As the duct strength increases the entry angle attenuation at 50MHz is greatly increased indicating that weak ducts may be better for propagation at 50MHz. Propagation at 50MHz using NZ television has been noted on many occasions when the Hepburn Charts [6] indicate VHF/UHF propagation is likely. At the same time the local Ionogram data showed very little sparodic E activity [7] providing additional evidence of propagation at 50MHz via an elevated duct.

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.

We can now cover the last few misunderstandings introduced at the beginning:

5) *Duct is frequency dependent:* Yes, the frequency dependence is related to the duct strength and the radio wave entry angle.

6) *Coupling into the duct is only at the ends:* No, 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.

7) *Your antenna must be in the duct:* No, but clearly closer to the duct is better and is illustrated by the higher placed stations working more DX via ducts.

8) *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 an evaporate duct also occurs.

VI. 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:

1) *Elevated ducts remain elevated, they form and break up at a given height.*

2) *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.*

3) *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.*

4) *Ducts act more like a boundary layer by repeatedly refracting VHF and UHF signals resulting in long distance propagation.*

5) *The smaller the entry angle (closer) to the duct the better the coupling.*

6) *Characterizing the duct as a "wave guide" is probably incorrect given the evidence.*

7) *The duct is frequency dependent, band pass, the low frequency cut-off being determined by the entry angle and the high frequency cut-off determined by the duct strength.*

8) *Surface evaporation ducts occur over water, surface radiation ducts occur over land.*

9) *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.*

Acknowledgment

Tele-IP Limited is acknowledged for providing data from its StratoSonde SODAR for use in this paper. The many contributions from other amateurs by way of observations and just being there to make a contact are also acknowledged.

References

[1] http://weather.uwyo.edu/upperair/sounding.html
[2] AREPS, http://sunspot.spawar.navy.mil/2858/index.html.
[3] R. Blackwell et. al, *The VHF/UHF Handbook*, UK, DIR Publishing, First Ed, 1992. pp. 2-23–2-24.
[4] ITU-R Study Group 3, Recommendation P.530-1999.
[5] VK3UM Software Suite, http://www.qsl.net/vk3bez
[6] William Hepburns VHF/UHF Tropospheric Ducting Forecast at http://home.cogeco.ca/~dxinfo/tropo.html
[7] IPS Inogram Viewer http://www.ips.gov.au/Main.php?CatID=6