AIRCRAFT ENHANCEMENT OF VHF/UHF SIGNALS

— towards a propagation model

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In the July 1985,issue of Amateur Radio[1], Doug McArthur VK3UM, detailed results of observations, carried out over some two years, of unusual signal level 'enhancements' of VHF and UHF troposcatter signals over the Melbourne-Sydney and Melbourne-Canberra paths. This paper examines the results reported, along with other information gleaned about the phenomenon from the many other amateurs exploiting the propagation, and sets forth a preliminary 'model' of the propagation mechanism. Suggestions for further experimental investigations and measurements are advanced.

Being a long-time VHF/UHF enthusiast, with a keen interest in propagation, my curiosity was naturally aroused by Doug McArthur's article in the July 1985 issue of AR[1]. In some detail, Doug describes how, during attempts at making contact via tropospheric scatter on 144MHz between his station, in Melbourne, and Gordon McDonald VK2ZAB, in Sydney, a path some 700km long, massive 'lifts' in the signal level lasting some minutes were evident at times. The same effect was observed, fortuitously, on the Melbourne-Canberra path. This led to the effect being correlated with the passage of domestic passenger aircraft more or less passing through the path mid-point between the stations.

Subsequent to the early observations, many other stations exploited the 'newly-discovered' propagation mode and a series of co-ordinated contacts threw up a great deal of data about the phenomenon. In addition, the same paths initially exploited on 144MHz were successfully attempted on 432MHz, with similar results.

In summary, here are the observations reported:

a. Predominantly, the phenomenon has been exploited with south-bound aircraft.

b. Enhancement periods on the Melbourne-Sydney path, for 144MHz, are about 2-7 minutes. On 432MHz the period decreases to about half or two-thirds.

c. Signal level 'lift' observed is estimated to be 30-60dB. Subjectively, signal lift on 432MHz appears greater than on 144MHz.

d. No 'flutter' fading of signals is observed.

e. Signal level lift and period of enhancement are dependent on upper-air wind conditions. Period and signal strength are best when upper-air conditions are 'quiet', worst when 'turbulent'. Diurnal (daily) and seasonal effects are noted (though subjective); winter providing better enhancements on average than summer, and evenings being better than daytime or morning.

f. Stations in Frankston (Melb) hear stations in Sydney some two to three minutes **earlier** *than VK3UM, who is located about 40km closer to Sydney.*

g. Best enhancement periods are observed when stations lie close to the line of the aircraft track.

h. Stations located up to 60km distant (possibly more), orthogonal to the aircraft track, have exploited the phenomenon.

i. 'Backscatter' propagation is noted between Canberra and Sydney stations while exploiting propagation on south-bound aircraft. This phenomenon is only noted during exceptional 'lift' conditions.

j. Lengthened enhancement periods are observed when two (or more) aircraft pass at 8-15 minute intervals.

k. The size and type of aircraft seemingly has little bearing on the enhancement characteristics, although jet or turbo- prop aircraft are known to be always involved.

That gives a fairly complete picture of the aircraft enhancement propagation phenomena.

MECHANISMS PROPOSED

Three possible mechanisms were proposed by McArthur:

i. Direct reflection from the body of the aircraft.

ii. Reflection from the condensation trails left by the aircraft flying above 30 000 feet (about 9km).

iii. Refraction caused by the air turbulence wake left by such aircraft. (Temperature heating effect or vortex turbulence).

From personal discussions with Gordon McDonald VK2ZAB, he favours i. as the explanation.

The model of the propagation mechanism I propose to explain the characteristics of the phenomena is based on iii. First, however, let me explain why I dismiss i. and ii.

I do not think reflection from the aircraft is the mechanism involved, nor does it contribute to the observed signal levels. I have argued this in another article, published in 6UP recently[2], but let me re-cap here. There are two reasons why I believe direct aircraft reflection is not a consideration:

I. Consider Figure 1. If the aircraft is acting as a mirror, the reflection of the signal will have a 'foot-print' on the ground that travels at twice the speed of the aircraft and **in the same direction.** *The observation in f. above directly contradicts this and an aircraft reflection model does not explain this important observation of which I have first-hand experience[2].*

II. There are widely differing opinions, even in the engineering texts, as to how to calculate the signal levels after reflection from the aircraft. Picquenard[3] gives a relatively simple 'mirror' reflection method for calculating the signal strength. Consider Figure 2. Picquenard indicates the total path loss, from A to the 'mirror' to B, is the sum of the individual path losses. This model takes the 'mirror' to be simply a re-radiator of the energy illuminating it.

Take the VK3UM-VK2ZAB case. I calculate the distance between the stations to be about 708km. For the 'mirror' at path midpoint (0.5d), the distance between A and the 'mirror' is 354km. From [3], the free-space path loss for this distance is calculated from:

$$\text{Loss} = 32.4 + 20\log(d) + 20\log(f)$$

where — d is distance in km
f is frequency in MHz

On 432MHz, we get:

$$\begin{aligned}\text{Loss} &= 32.4 + 20\log(354) + 20\log(432)\\ &= 32.4 + 20(2.55) + 20(2.64)\\ &= 32.4 + 51 + 52.8\\ &= 136\text{dB (within 1dB)}\end{aligned}$$

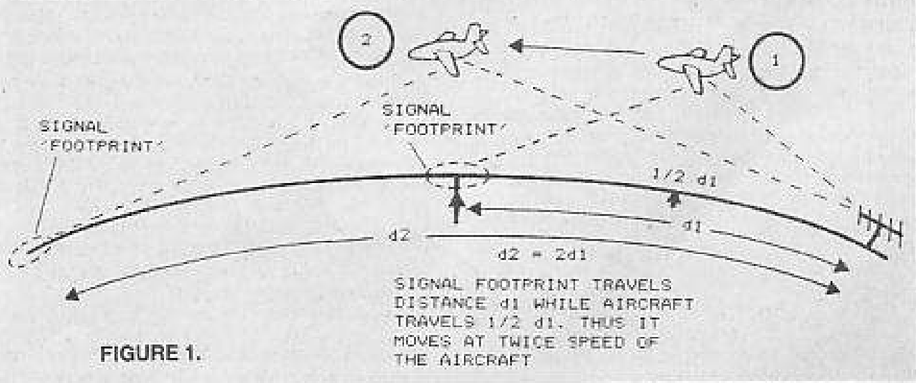

FIGURE 1.

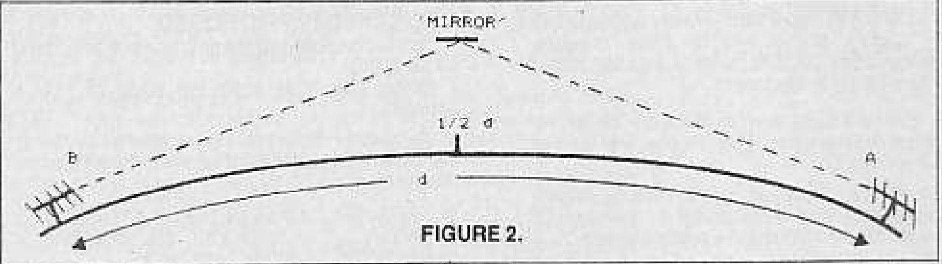

FIGURE 2.

Thus, total path loss is twice that, or 272dB. Note that the EME path loss is 262dB on 432MHz[4], which makes the 'mirror' model 10dB worse off under these circumstances providing Picquenard's methodology applies.

Even if the 'mirror' were able to focus the signal, thus providing an improvement in signal strength by concentration of the beam reflected, this model of the mechanism cannot apply as so little power falls on the 'mirror'.

In addition, stations off-track would reflect a foot-print off-track on the opposite side of the aircraft track and the observations do not show this.

As for ii., aircraft vapour trails comprise atmospheric water vapour. Radio waves travel slower in such a medium and thus a terrestrial VHF or UHF radio wave impinging on the vapour trail would be refracted upwards, away from the ground. In addition, vapour trails are not always present where signal enhancement is experienced.

For those who might consider some form of reflection from a possible ionised trail left behind by the aircraft exhaust, let me point out that the recombination time of atmospheric ions at the aircraft altitudes involved would be extremely short. Remember, the aircraft fly well below the minimum height of the ionospheric D layer.

Now, let me set down the geometry of a variety of the paths exploited by different stations as this is important to my hypothesis and gives a more 'visual' picture of what is going on.

GEOMETRY OF PATHS

An overview of the Melbourne-Canberra-Sydney path is shown in Figure 3. The Sydney-Melbourne (south-bound) aircraft track has a bearing of about 50-51 degrees (from Melbourne), which is pretty well along the Great Circle path joining Melbourne and Sydney. Canberra lies just to the east of the track. The aircraft will take an actual flight path that may be a few kilometres east or west of this track at times, but that only contributes a minor, if at all noticeable, variation, as we shall see later.

The Melbourne-Sydney aircraft track takes a bearing slightly northward of the southbound track, flying some 50km or so to the west of Canberra before turning east again on the approach to Sydney. The aircraft fly at heights between 30 000 feet and about 45 000 feet, or roughly 9km to 13.5km altitude.

From a mass of data about reported contacts between stations[5], I have sorted out some particular contacts that provide a picture about the details of the path geometry. The paths chosen are listed in Table 1, in which I have listed the point-to- point distances involved. Note the large path distance variation observed, from 360km to 750km. I would point out that these are not necessarily the maximum or minimum limits.

Using a set of ICAO World Aeronautical Charts covering the Melbourne-Canberra-Sydney path[6] I plotted the general track of the Sydney-Melbourne flights involved and then measured the orthogonal distance of four off-track locations of Victorian stations who had exploited the enhancement phenomena to get an idea of the size of the 'foot-print' of signals from Sydney and Canberra. The geometry of the idea is shown in Figure 4, and the orthogonal distances listed in Table 2.

It is apparent from observations and chart plotting that VK3UM, at Chirnside Park, in Melbourne, is located very close to the line of the general aircraft track. How fortuitous! It seems, also, that some Sydney stations are similarly positioned. *(Note, though, that aircraft descending for a landing at Melbourne airport, Tullamarine, turn off-track well to the north of VK3UM).*

The vertical geometry of the situation is illustrated in Figure 5. Essentially, this is an optical model of the situation. The station at A will 'lose sight' of the aircraft when it passes point M. Likewise, the station at B will lose sight of the aircraft when it passes point L.

Using this diagram, you can fairly well estimate the time taken for an aircraft to traverse M-L and the 'seeing angles' (a and b) for given path lengths, knowing the typical aircraft cruising speeds and altitudes for the paths involved as reported in [1]. The various aircraft that fly the Sydney-Melbourne route cruise at speeds that range from around 800km/hr to 910km/hr (from data supplied by the various carriers).

From [7], I worked out typical tangential distances station-to-aircraft and was able to make good estimates of the time two stations could 'see' an aircraft, as well as the other parameters. As you would expect, the parameters vary with path length, aircraft cruising speed and altitude and the altitude of the stations.

Typically, on the Sydney-Melbourne path, stations are able to 'see' the aircraft for periods of around five to seven minutes. On the Canberra-Melbourne path, stations are able to 'see' the aircraft for some 18-23 minutes (ignoring the obscuration of Black Mountain for some VK1s). We'll see how this fits into the reported enhancement periods shortly.

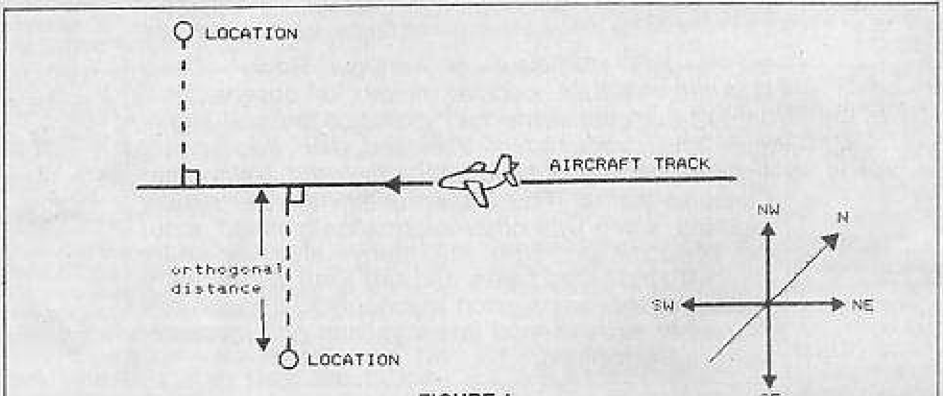

FIGURE 4.

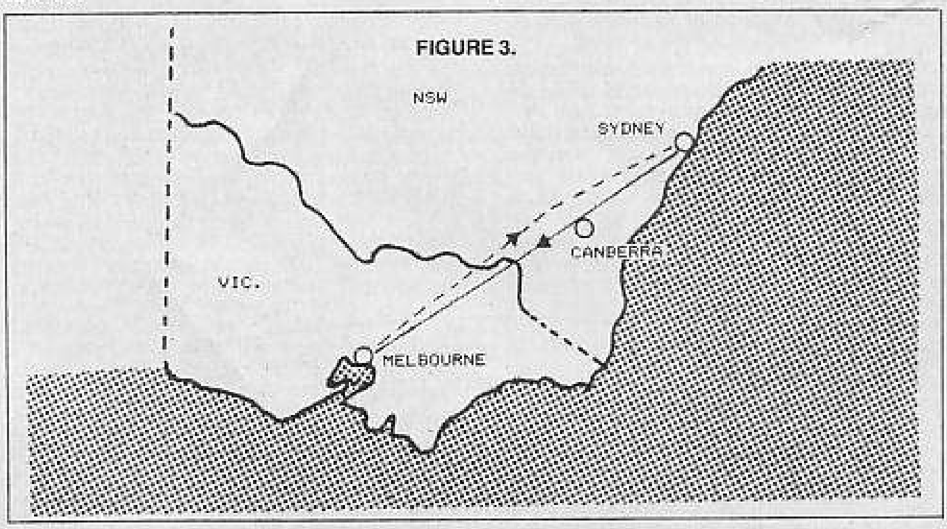

FIGURE 3.

THE SIGNAL 'FOOT-PRINT'

By timing the first appearance of a signal at two separated stations located at one path terminal[2, 5], it is apparent the signal foot-print travels **toward the aircraft** at about the same speed as the aircraft is flying. By timing the period of the enhancement — from acquisition of the signal to loss of signal — one gets an idea of the longitudinal width of the foot-print at a particular station location. By taking into account the orthogonal distances listed in Table 2, one gets an idea of the lateral extent of the foot-print.

From putting together more or less simultaneous observations by Melbourne stations located on-track and off-track[5], it seems the lateral and longitudinal width varies with upper-air wind conditions. The foot-print apparently shrinks when upper-air conditions are turbulent.

Well, just how big is that foot-print and what might its shape be?

For the Sydney-Melbourne path I would judge the foot-print to be roughly elliptical, or

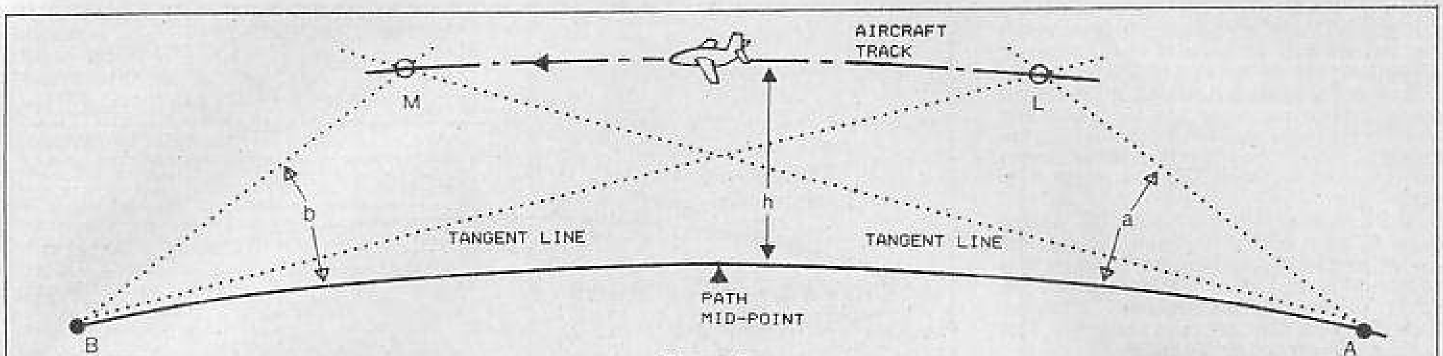

Figure 5

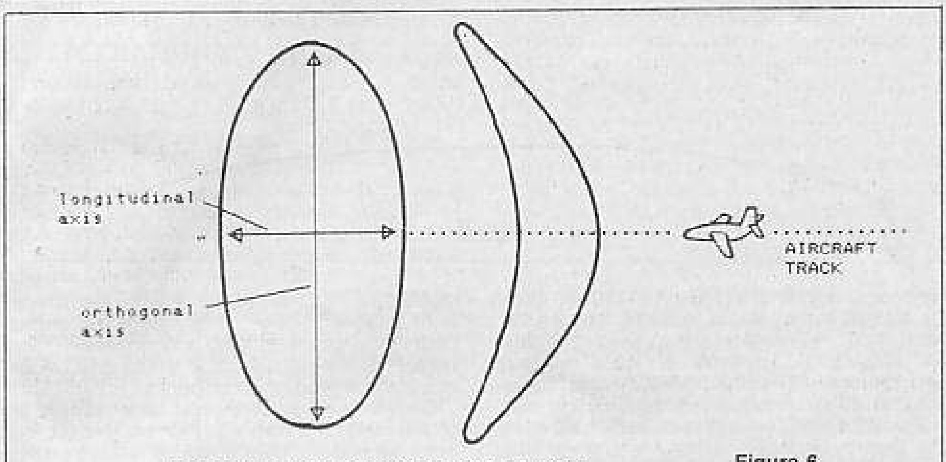

Figure 6

perhaps an ellipse 'bent' into a crescent shape (not unlike a boomerang!), see Figure 6. Under conditions of best enhancement, its longitudinal axis seems to be around 60-70km, and its orthogonal axis somewhat greater than 120km. When conditions are 'bad', it seems to shrink so that its longitudinal axis is only about 6km and its orthogonal axis about 25-30km. See Figure 7.

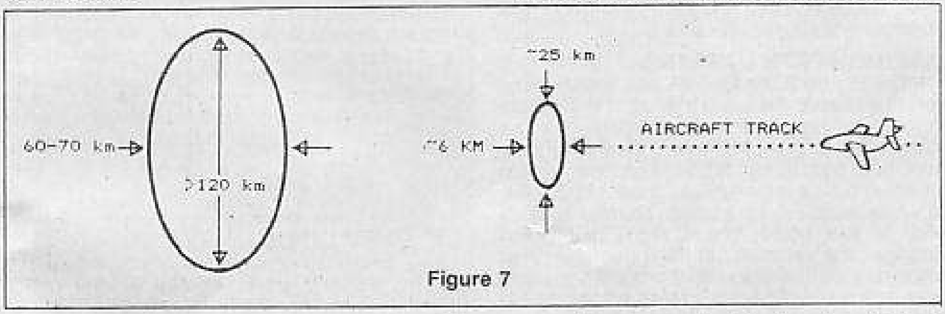

Figure 7

For the Canberra-Melbourne path, the longitudinal axis under best conditions appears to be around 150-200km, although the orthogonal axis seems to be about the same (ie a circular foot-print), judging from the observations of David Tanner VK3AUU[5]. Under bad conditions, the minimum foot-print seems to be much the same as for the Sydney-Melbourne case. This isn't to say that, if a Melbourne station first works a Sydney station, followed by a Canberra station, the successive foot-prints in Melbourne will be of comparable sizes resulting in similar enhancement periods.

With such a foot-print model, stations located more or less on-track with the aircraft flight path will always observe longer enhancement periods, while those off-track will experience shorter enhancement periods. For stations well off-track (eg VK3AUU), conditions have to be good if they are to make it at all. Figure 8 illustrates the typical enhancement periods reported under good conditions as the foot-print passes over stations on-track and off-track.

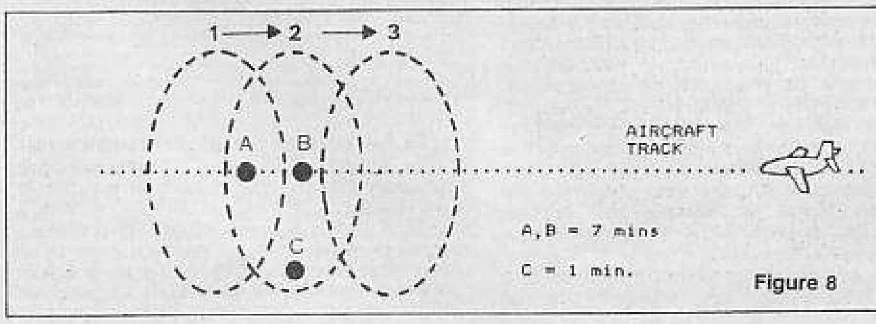

Figure 8

A PROPAGATION MODEL

If the aircraft is not itself reflecting sufficient signal to account for the observed phenomena, *what mechanism returns the signal to earth in the manner observed?*

I think the aircraft engine exhaust — largely superheated air — is responsible. It seems very little is known about what these aircraft leave behind as they traverse their paths through the sky. From data obtained by Don Bradbury VK3YV[8], the exhaust temperature of the jet engines fitted to the variety of aircraft flying the route is around 650 degrees Celsius or so, but this decreases rapidly to about 200 degrees C as it passes the aircraft tail (for wing-mounted engines, eg on 747s, 737s, A300s, etc) at the altitudes involved. *But what happens to all that hot air?*

The aircraft develops a turbulent wake; this is well known. What seems not to be well known are the parameters of the aircraft wake at altitudes of 9km and above. A recent issue of the Aviation Safety Digest[9] gives a few clues, but is not all that helpful. The particular article detailed measurements of the 'vortex tube' created by jet aircraft, measured at quite low altitudes. Apparently, the vortex tube descends behind the aircraft at a rate of around 500 feet/minute to a distance of around 900 feet below the aircraft. This seems to relate more to what the aircraft does to the air than what the engine exhaust contributes. Draw a blank there.

What I think happens is this: although the jet engine exhaust cools rapidly a first, the cooling rate will slow down rapidly; the hot exhaust air left behind will then expand, creating a 'bubble' of air at a temperature well above that of the surrounding air (which will be typically at -30 to -40 degrees Celsius). A radio wave impinging on this hot air bubble from below will travel faster in the hot air than in the cold air and thus be refracted toward the ground. The amount of refraction depends on the rate of change of temperature from outside the bubble to inside the bubble. From Collier[10], a rate of change of temperature with height of three degrees Celsius per 100 metres will cause a refraction at 144MHz of perhaps three to five degrees in angle, possibly more.

Now, the temperature inside the bubble need not be too much greater than the outside air temperature to provide the necessary refraction. Until we can obtain some direct data on the parameters,exactly what is happening there will remain a mystery.

Accepting that the signal is refracted by the hot bubble being dragged along behind the aircraft, *why does the signal foot- print travel towards the aircraft?*

Consider Figure 9. As the aircraft drags its bubble through position 1 (equivalent to L in

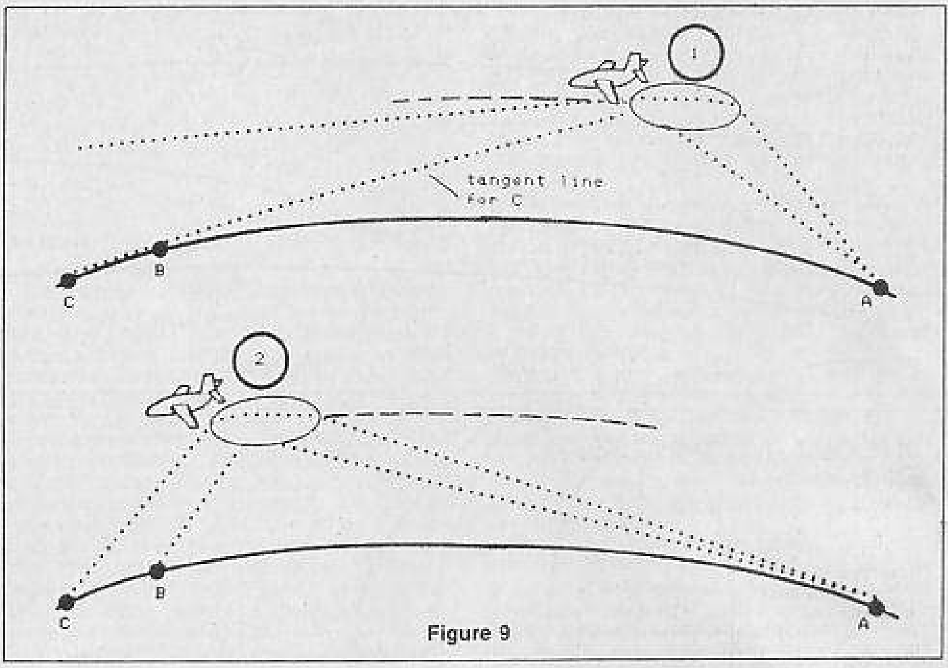

Figure 9

Figure 5), it will refract the signal as shown, and station C will commence to hear A. When the aircraft has progressed to position 2 (equivalent to M in Figure 5), station B hears A. Communications will last so long as the station at one end of the path can 'see' the bubble and also that the angle between the ground and the bubble is not so great that the bubble cannot refract the signal sufficiently to return it to earth.

On the Sydney-Melbourne path, the 'seeing angle' to the bubble (a in Figure 5), when the aircraft passes through position 1 (Figure 9) is typically around 1.25 to 1.5 degrees and the bubble can be seen for around 5-7 minutes, depending on the aircraft's altitude. This accords well with the observations.

On the Canberra-Melbourne path, while the bubble can be seen from both ends for around 20 minutes, the elevation angle for one end of the path eventually becomes too great for the bubble to refract the signal to ground. Typically, I estimate the elevation angle at loss of signal to be five or six degrees.

BUBBLE DIMENSIONS

How long is the bubble and what diameter is it? The bubble trailing behind the aircraft will eventually dissipate its energy through convection and radiation. Under turbulent upper-air conditions, it will be literally blown away.

The 'length' of the bubble, as 'seen' by the radio wave, depends on the bubble having sufficient refractivity to return the signal to ground. A rough estimate obtained by correlating subsequent Canberra-Melbourne contacts with Sydney-Melbourne contacts for VK3UM, puts the bubble length under best enhancement conditions at around 60km to perhaps 80km. The diameter is much harder to estimate.

One could possibly get an estimate of bubble diameter from the width of condensation trails. It seems entirely reasonable that the condensed water vapour would mark the lateral boundaries of the base of the bubble, but not necessarily the longitudinal extent. Water vapour, once condensed in the upper atmosphere under the right conditions, is quite stable, whereas heated air will dissipate by radiation and convection.

By estimating the angle subtended by aircraft con trails at altitudes around 10km or so, I would put the diameter of the bubble to be around a half kilometre to perhaps two kilometres within about 20km behind the aircraft. I will admit this is a bit of a fudge, but we need some starting point.

Diurnal and seasonal variation of upper-air conditions are reasonably well known and would affect the bubble accordingly. Lower air temperatures in winter would mean a greater temperature differential in the bubble, and quite possibly generally larger bubbles. This would account for the reported better conditions in winter compared to summer. A similar explanation applies to diurnal variations, in broad terms.

SIGNAL STRENGTHS

To get a reasonable numerical model to explain signal strengths is a difficult problem indeed. One of the fundamental problems here is lack of accurate measurement of the signal level 'lift' observed. The majority of reports are the usual amateur 'S-meter' (rhymes with 'guess-meter') reports. All we can really deduce is that S9 is 'quite strong' and S3 is 'quite weak'. McArthur[1] provides an estimate of the signal level **variation,** being some 60dB, which gives some clues. If, enhancement levels can vary this much, then the 'lift' provided should be at least that or greater, providing the reported estimate is within at least 10dB. From[5] I'm fairly confident of that.

If the troposcatter path loss for Sydney-Melbourne is around 235dB on 144MHz[11], then the aircraft is dragging a 'window' through the path, reducing the path loss to around 175dB. As suggested[1], stations of quite modest performance will have sufficient system gain to overcome that and achieve communications. *But what about the reported back-scatter on the Sydney-Canberra path?* I would say the signal travels twice through the bubble, being scattered from the ground at the far end of the path. As observed, it requires a 'good' enhancement and well-equipped stations.

From experience, ground back-scatter loss at the frequencies concerned is on th order of 30-40dB. This would subtract from the lift provided by the enhancement, but well-equipped stations can readily overcome the extra loss, as has been reported[1].

I hope o tackle a numerical 'guesstimate' of how the observed signal strengths are obtained in a subsequent article.

MAXIMUM PATH LENGTHS

From Figure 5, reference[7] and knowing the sort of altitudes the aircraft fly at, it is possible to predict maximum path lengths, For an aircraft flying at 40 000 feet (12km) or above, maximum path length is on the order of 900km for an enhancement (under 'good' conditions) of a minute or less for stations on-track at each end. If you could 'chain' flight paths and arrange the aircraft to fly through their respective path midpoints at around the same time, you could get a two-aircraft enhancement and extend the path to around 1800km.

McArthur[1, 5] reports observations of VK4LC which suggest just such a possibility for Brisbane-Sydney/Sydney-Melbourne flights.

SUGGESTIONS FOR EXPERIMENTS

I would suggest it is now important to obtain two sets of measurements: calibrated signal strengths and co-ordinated time observations of the foot-print parameters. In addition, the paths should be attempted on other bands, such as 50MHz and 1296MHz.

A calibrated step attenuator at the receiver front end, or in some convenient portion of the receiver chain, could be used to measure peak 'lift' values quite simply. Upon observing the maximum signal lift, simply add enough attenuation to reduce the signal to scatter levels or below the noise.

Chart recorder observations of beacons or a continuously transmitting station would be invaluable. Simultaneous chart recordings from stations at one end of a path, separated both longitudinally and orthogonally with respect to the aircraft track would also tell us much about the signal foot-print.

Co-ordinated simultaneous tape recordings of one station by an array of stations at the opposite end of a path would be relatively easy to attempt using readily available equipment. Each listener would need a stereo tape recorder and an HF receiver in addition to his VHF/UHF receiver. The station at the other end of the path would be recorded on one channel of the tape, while VNG or other time standard station is recorded on the other channel. By co-ordinating on another band or channel, all recorders would be started before acquisition of signal by the furtherest away station, and stopped after loss of signal by all receiving stations.

Such experiments would tell us a great deal and likely contribute much toward working out a numerical model for the propagation mechanism.

To paraphrase a common expression — the foot-print is in your court, gentleman!

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TABLE 1 — Path Distance Parameters.

LOCATIONS	APPROX DISTANCE
VK2ZAB/Berowra to Frankston (eg VK3ZBJ et al)	750km
VK2ZAB/Berowa to Drouin (VK3AUU)	720km
VK2ZAB/Berowa to Chirnside Park (VK3UM)	708km
VK3UM/Chirnside Park to Sydney (eg VK2BE et al)	678km
VK3UM/Chirnside Park to Canberra (eg VK1BG et al)	466km
VK3UM/Chirnside Park to Adaminaby (VK2ZRE)	360km

TABLE 2 — Off-Track Parameters.

LOCATION	ORTHOGONAL DISTANCE/DIRECTION
Drouin (VK3AUU)	52km/SE
Adaminaby (VK2ZRE)	45km/SE
Geelong	25km/NW
Frankston	22km/SE

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