AIRCRAFT ENHANCEMENT – SOME INSIGHTS FROM BISTATIC RADAR THEORY

This paper is an abridged version of one originally presented at GippsTech 2000, the annual Australian Conference designed to encourage participation in VHF, UHF, and Microwave amateur operations that was also published in CQ VHF magazine in the Fall 2003 Edition.

By Rex Moncur, VK7MO

Aircraft enhancement is widely used on the East coast of Australia for VHF and UHF contacts in the range 400 to 800 km. It produces enhanced signals for typically a few minutes that are 20 to 30 dB more than would be expected based on radar reflection or tropo scatter. The key difference between aircraft enhancement and normal radar reflections is that the aircraft must be closely in line between the two stations to achieve the enhancement.

This paper draws on the literature on bistatic radar (transmitter and receiver located a large distance apart) to give some insights into aircraft enhancement. Skolnik[1] gives as an example the fact that for a sphere of radius 10 times the wavelength forward-scatter is enhanced by 36 dB compared to back-scatter as applies to the more normal monostatic radar (transmitter and receiver co-located). While a sphere of this size, 40 metres diameter at a wavelength of 2 metres, would present a much larger area than the largest aircraft the example does show that large enhancements can be produced.

In terms of a large aircraft, such as a 747 front on, bistatic radar theory shows that while the normal radar back-scatter area is only a little more than 100 square metres the effective forward-scatter area at two metres is of the order of 30,000 square meters. At 70 cms the forward-scatter area can reach 240,000 square metres.

I have applied the theory to simple shapes (sphere and sections which approximate the wings, cabin, and tail of example aircraft) rather than the complex shape of an aircraft. Nevertheless, I believe it does give some useful insights that help explain some of the observations of amateurs who have experimented with aircraft enhancement. For example, it does explain significant signal enhancements, why larger enhancements might be obtained at higher frequencies and also why large enhancements only occur when the aircraft is close to in line between the stations.

Information is given on the construction of a simple model based on a map, tracing paper and a drawing pin that allows the prediction of aircraft enhancement from known flight paths.

Background

In 1985 McArthur, VK3UM [2] reported peaks of 30 dB or more enhancement of 144 MHz signals between Melbourne and Sydney related to aircraft, which lasted from a few minutes to tens of minutes. He stated that the enhancement was significantly greater than determined by the radar equation.

However, before we look too hard to explain aircraft enhancement we need to understand what we mean by it. For example, do we mean enhancement over what is calculated by the normal radar theory or over the average tropospheric scatter conditions or above the noise in our receiver, etc. Partly because it is easier, but also because it focuses on the reason for enhancement I have chosen to try and answer the question as to:

> **why and by how much the enhanced signal is greater than calculated by normal (monostatic) radar theory?**

Looking at McArthur's article he reported increases of 30 dB or more related to aircraft and also stated he could observe signals he could relate to the radar equation which were 3-6 dB above forward scatter (tropo scatter) which was itself 3 dB above the noise. This equates to enhancements above the normal radar equation of 21 to 24 dB or more.

McDonald, VK2ZAB [3,5&7], Harrison, VK2ZRH (then VK2ZTB) [4] and Cowan, VK1BG [6,8] have vigorously debated the mechanisms for aircraft enhancement, with proposals ranging from reflection from the undersurface of the aircraft to refraction in the hot air produced by jet engines.

McDonald's thinking has progressed since he proposed reflection from the undersurface of the aircraft in his October 1985 article[5]. In his May 1989 article, McDonald[7], highlighted the link to bistatic radar theory. McDonald has also advised that Kent Britain, WA5VJB, discussed this link as early as 1986.

I will quote from the literature on bistatic radar later in this section. But, first some explanation of bistatic radar.

A bistatic radar is one in which the transmitting and receiving sites are at different locations which is the situation with aircraft enhancement (the more usual radar is monostatic radar where the transmitter and receiver are co-located). An interesting feature of bistatic radar is that when the scattering of the signal takes place at a target close to 180 degrees (forward-scatter) there is substantial enhancement compared to the back-scattered signal as applies to monostatic radar. The following diagram copied from Barton[9], page 504, shows the situation.

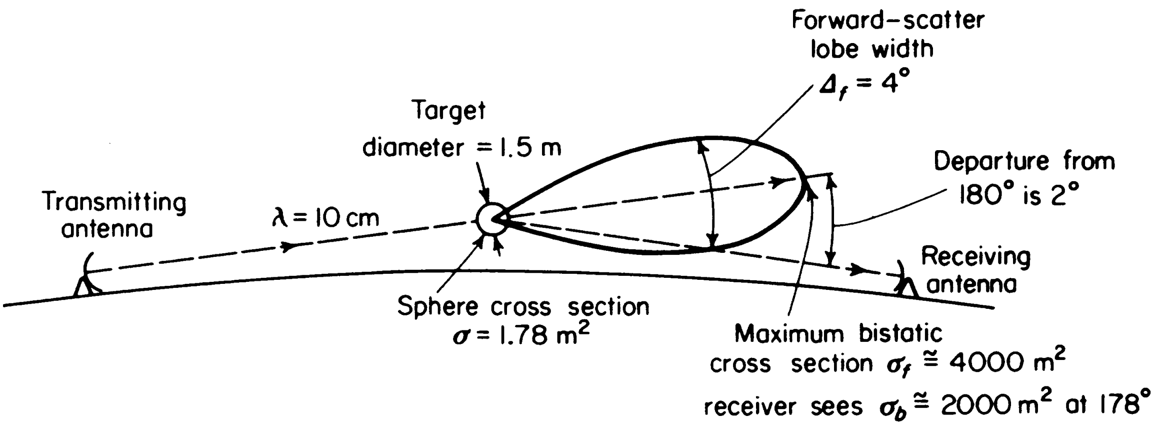

Figure 1: An example of bistatic radar where the transmitter and receiver are close to alignment, copied from Barton[9]

The extracts below from Barton[9], pages 121 and 503, give some idea of the effect:

> "An important characteristic of bistatic radar is found when the angle between the transmitter and receiver paths approaches 180 degrees. In this 'forward scatter' case, the bistatic cross section may greatly exceed the normal backscattering coefficient. This is due to the fact that the total power in the forward-scatter lobe is equal to that scattered over the remainder of the 4π steradians around the target"
>
> "...the bistatic cross section may be increased by a large factor, as compared with the normal, monostatic radar cross section of the target. This increase is due to the relatively larger 'forward scatter' of the target, shown by Siegel [10] to be equal to:
>
> $$\sigma_f = 4\pi A^2/(\lambda^2) \quad * \qquad \text{Equation 1}$$
>
> where A is the projected area of the target and λ is the radar wavelength.
>
> Note: Equation 1 applies where the dimensions are much larger than a wavelength.

One way to visualize the enhanced signal is to think of an ocean wave coming to a small island. The wavefront diffracts around both sides of the island and at point some distance beyond the island you see the two wavefronts adding together to give an enhanced wave. In the case of aircraft enhancement we are doing the same thing in three dimensions so the energy is adding from waves from both sides the top and the bottom and in fact all around the object to produce an significantly enhanced wave.

Forward-Scatter Enhancement

In the case of a sphere (radius r) the ratio of the forward-scatter target cross section to the back-scattered target cross section, which I will call forward-scatter enhancement f_e, is given by Skolnik [1], as:

$$f_e = (2\,\pi\, r/\,\lambda)^2. \qquad \text{Equation 2}$$

Equation 2 is applied in Table 1 to give examples of the enhancement of forward-scatter over back-scatter for spheres of various diameters at wavelengths of 2 metres, 70 cm and 23 cm.

Radius of Sphere	Projected Area of Sphere	Wavelength		
		2 m	70 cm	23 cm
Metres	Square Metres	dB	dB	dB
1	3	10	19	29
5	79	24	33	43
10	314	30	39	49

Table 1: Enhancement in dB of forward-scatter radar cross-sections compared to back-scattered cross sections for spheres at different wavelengths.

However, before we get too excited about near 50 dB enhancements at 23 cm we must take account of that general principle that you don't get anything for nothing. In this case the penalty for more enhancement is that the solid angle in which forward enhancement occurs reduces as the enhancement increases. Figure 1 shows the importance of keeping the scattering angle within the forward scatter lobe if useful enhancement it to be achieved. This means that the aircraft must fly close to inline between the receiver and transmitter. Figure 1 also shows that for practical radio paths the height of the aircraft plus the curvature of the Earth will limit the ability to keep the scattering angle small. This in turn limits the amount of enhancement that is possible, particularly at higher frequencies where the forward scatter lobe becomes much narrower.

Width of Forward Scatter Lobe

Barton[9], page 504, gives the width of the forward-scatter lobe at the 3 dB points, Δf, as:

$$\Delta f = \lambda / L \text{ radians} \qquad \text{Equation 3}$$

where L is the length or diameter of the target in the plane in which Δf is defined

While the 3 dB point is a useful measure of the width of the forward lobe is should be noted that forward-scatter signals can still be received at larger angles, but they will be weaker. That said, we will use the 3 dB point from 180 degrees, or angle of departure, Δd, which is half Δf as a useful indicator. Substituting for Δd and converting Equation 3 to degrees gives:

$$\Delta d = \lambda * 45/(r * \pi) \text{ degrees} \qquad \text{Equation 4}$$

Table 2 applies Equation 4 to give examples of the angles of departure that result from using spheres of different sizes.

Radius of Sphere	Wavelength		
	2 m	70 cm	23 cm
Metres	Degrees	Degrees	Degrees
1	28.6	10.0	3.3
5	5.7	2.0	0.7
10	2.9	1.0	0.3

Table 2: Angle of departure from 180 degrees at the 3 dB point for spheres at different wavelengths.

Essentially Table 3 shows us that the very high level of enhancements in Table 1 for large spheres and at very short wavelengths are only possible if the angle of departure is very small. In practice very small angles of departure cannot be achieved at distances of a few hundred km because of Earth curvature and aircraft height and thus this limits the enhancement which is possible.

Now we can use Equation 4 to define the radius of a sphere in terms of Δd and substitute in Equation 2 to derive the maximum forward enhancement in terms of the angle of departure:

$$F_e = (90/\Delta d)^2 \qquad \text{Equation 5}$$

Putting the maximum Forward Enhancement into dB and subtracting 3 dB to find the forward enhancement at the departure angle or the receiver, gives:

$$F_{er} = -3 + 10 * \text{Log}\left((90/\Delta d)^2\right) \text{ dB} \qquad \text{Equation 6}$$

Using geometry, and assuming a target altitude of 10 km, enhancement at the mid-point of the path and taking account of radio refraction with the 4/3rds Earth radius rule we can calculate the angle of departure as shown in Table 3. Substituting the angles of departure thus determined in Equation 6 gives the maximum forward scatter enhancement at the receiver for a sphere as also shown in Table 3.

Distance between Transmitter and Receiver km	Angle of departure, Δd Degrees	Maximum Forward Scatter Enhancement at Receiver dB
100	22.9	8.8
200	12.1	14.4
300	8.6	17.3
400	7.1	19.1
500	6.3	20.1
600	5.8	20.7
700	5.6	21.1
800	5.6	21.2
900	5.6	21.2
1000	5.7	21.0

Table 3: Angle of departure resulting from a target height of 10 km and Earth curvature based on 4/3rds rule and resulting maximum forward scatter enhancement from spheres for different distances. Target is at mid-point.

Table 3 shows us that for the typical aircraft enhancement paths of several hundred km the angle of departure will be around 5 to 7 degrees and the maximum forward enhancement for a sphere compared to the back-scatter is around 19 to 21 dB. This is encouraging as it in the order of that observed by McArthur.

Now we can use Equation 4 to determine the maximum radius of a sphere in terms of angles of departure:

$$r = \lambda * 45/(\Delta d * \pi) \qquad \text{Equation 7}$$

Table 4 applies Equation 6 to give the maximum radius spheres to be within the 3 dB beam-width at an angle of departure of 7 degrees.

Wavelength	2 m	70 cm	23 cm
Radius of Sphere metres	4.09	1.43	0.47

Table 4: Maximum radius sphere to allow 3 dB points of forward scatter lobe within 7 degrees.

An Aircraft compared to a Sphere

In most cases where aircraft enhancement has been observed the aircraft presents a front or rear aspect as a scattering target. The nose is likely to be equivalent to a sphere and exhibit similar characteristics to those examined above. Equation 1 shows that it is the projected area that determines the level of forward scattering. Thus an aircraft will have the same characteristics coming or going and its cabin, if it were circular, would be equivalent to a sphere of the same radius.

Using Table 4 we can see that in order to use the main forward scatter lobe we need to have aircraft with cabins less than 4 metres in radius at 2 metres and substantially less at 70 cm and 23 cm. While the cabins of aircraft will be useful at 2 metres (even a 747 is just less than 4 metres radius in the vertical) most will be too large for the higher frequencies.

The wings, however, are a different proposition as they present an aspect that is many more times wider than their height. Returning to Equation 2, which determines the beam-width, this means that instead of a cone shaped forward lobe the wings will generate a fan shaped forward lobe with the fan in the vertical plane. This has the advantage that we can cope with larger angles of departure in the vertical where we have the problems of aircraft height and earth curvature. However, the downside is that the horizontal beam-width of the forward-scatter lobe is substantially reduced so the aircraft must be much closer to in line in the horizontal plane.

If we assume that the back-scattered area is close to the projected area then the forward scatter enhancement can be derived from Equation 1 as follows:

$$F_e = 4\pi A / \lambda^2 \qquad \text{Equation 8}$$

The projected areas for various sections in square meters of 747 and 737 aircraft, scaled from diagrams in Jane's aircraft[11], page 322 for 747 and Page 319 for 737, are set out in Table 5 together with the heights of the sections in metres in square brackets.

Aircraft	Cabin	Engines	Front Wings	Rear Wings	Tail	Total
747	38 [8]	18 [3]	54 [2]	10 [1]	7 [10]	127
737	14 [5]	7.5 [2]	12 [1]	3.6 [0.5]	2.4 [5]	39

Table 5: Projected areas (square metres) and heights in square brackets (metres) of various sections of 747 and 737 aircraft

Table 6 applies the total areas with Equation 8, converted to dB, to give the potential enhancement of these aircraft if there was no angle of departure.

Aircraft and Projected area in square metres	2 m dB	70 cm dB	23 cm dB
747 [127]	26	35	45
737 [39]	21	30	40

Table 6: Potential Enhancement for a 747 and 737 aircraft with no angle of departure

In practice it will not be possible to achieve the full enhancement listed in Table 6. This is because the beam-width of the larger vertical sections of the aircraft (eg tail) will be too narrow in the vertical plane to be used with an angle of departure of 5 to 7 degrees as required from typical aircraft enhancement contacts. We can modify Equation 3 for the length, L, of the scattering target and in terms of the departure angle (degrees) it will be:

$$L = \lambda*90/(\Delta d *\pi) \text{ degrees} \qquad \text{Equation 9}$$

Table 7 applies Equation 9 to find the maximum height of aircraft sections that will allow a beam-width of 7 degrees and thus be useful on a typical aircraft enhancement contact.

Wavelength	2 m metres	70 cm metres	23 cm metres
Section Height	8.2	2.9	0.9

Table 7: Maximum heights of aircraft sections to be useful (at the 3 dB point) with a 7 degree angle of departure

Table 7 tells us the size of sections that are useful for typical aircraft enhancement contacts at the 3dB points. Thus if the section is of the size shown only half of it is effective but if it is 50% or less it will almost fully contribute to the projected area.

From the combination of Tables 5 and 6 we can see that for a 747 at 2 metres the tail is too long to be useful and the cabin is on the margin (ie the 3 dB point) so we should allow only half. That is the effective projected area at a 7 degree departure angle should be reduced to 106 square metres. At 70 cm only the wings are useful giving an effective projected area of 64 square metres. At 23 cm much of the front wing is too large, much of the rear wing on the 3 dB point and the effective projected area drops to around 20 square meters.

For a 737 at two meters the tail must be deleted as it adds to the cabin like stacking two vertical antenna's – thus the effective projected area is 37 square meters. At 70 cm the tail and the cabin are too large so the projected area drops to 24 square metres. At 23 cm only the wings can be used and parts exceed the 3 dB points so the effective projected area drops to around 6 square metres.

The data for a 747 and a 737 are summarised in Table 8

Aircraft	2 m Square metres	70 cm Square metres	23 cm Square Metres
747	106	64	20
737	37	24	6

Table 8: Effective projected areas for 747 and 737 at a 7 degree angle of departure

Now enhancement, as I have defined it, is the ratio of the forward-scattered signal to the back-scattered signal (ie that for a normal monostatic radar) noting that the effective forward scatter area is somewhat less than the projected area as shown by Table 8.

$$\text{Enhancement} = 4*\pi*(A_f)^2/((A_b)*(\lambda)^2)) \qquad \text{Equation 10}$$

Where A_f is the effective projected area in the direction of forward scatter
A_b is the back-scatter area, approximated by the projected area

Table 9 applies Equation 10 to the data in Table 8 for A_f and Table 5 total areas for A_b to give the enhancement in dB of forward-scatter over back-scatter for a 747 and a 737 at 2 meters, 70 cm and 23 cm.

Aircraft	2 m dB	70 cm dB	23 cm dB
747	24.4	29.2	28.7
737	20.4	25.8	23.4

Table 9: Enhancement of Forward-scatter over Back-scatter for 747 and 737 aircraft at 7 degree departure angle

24.4 dB enhancement for a 747 and 20.4 dB for a 737 is in line with that which derives from the observations by McArthur[2] (21 to 24 dB or more). The results as presented in Table 9 show increases of around 5 dB from 144 to 432, consistent with a statement by McArthur[2] in relation to 432 MHz "..that the peak signals may be greater than 144 MHz." Note that at 23 cm the enhancement is lower as much of the projected area of the aircraft cannot be used at a 7 degree angle of departure.

It is interesting to now look at the beam-width in the horizontal plane as this, combined with the speed with which the aircraft passes through alignment, controls the duration of enhancement. The horizontal beam-width Δf is controlled by the length of the section in the horizontal plane and can be derived from Equation 3 as follows:

$$\Delta f = \lambda * 180/(L*\pi) \qquad \text{Equation 11}$$

In Table 10, Equation 10 is applied to look at the beam-width in the horizontal plane based on a wing span for a 747 of 64 metres and 737 of 28 metres. We also look at the cabin sections 747 (6.8 metres) and 737 (4 metres) as these can contribute a wider beam-width, although lower enhancement lobe at 2 metres.

Aircraft Section	Wavelength		
	2 m	70 cm	23 cm
	Degrees	Degrees	Degrees
747 wing 64 metres	1.8	0.6	0.2
737 wing 28 metres	4.1	1.4	0.5
747 cabin 6.8 metres	17		
737 cabin 4 metres	29		

Table 10: Beam-width of Forward scatter lobe at the 3 dB point for aircraft sections in the horizontal plane.

Table 10 shows us that when using scatter from the wing the aircraft needs to be aligned to within less than two degrees for a large aircraft at 2 meters which on a 500 km path means it must be within 8 km of alignment in the horizontal plane. The alignment needs to be much closer at higher frequencies and at 23 cm is less than 1 km. This indicates that at higher frequencies the period of enhancement as the aircraft passes through alignment will be reduced. Providing the same section of the aircraft is useable at the higher frequency then the reduction should be in proportion to the wavelength. This conclusion is at least partly supported by McArthur[2] who stated in comparison with 144 MHz "it appears that only one half to two thirds of the enhancement period exits at 432 MHz".

At two metres the cabin can contribute to the enhancement and it will provide a wider horizontal beam-width, but at a lower level. For example, with a 747 aircraft the effective projected area for radar-forward scatter of the cabin at 7 degrees departure angle is around half of the actual (ie about 20 square metres). Applying Equation 8 gives a wider enhancement of about 10 dB, compared to the peak enhancement of 24.4 dB. For a 737 most of the cabin will be effective at two metres giving a wider enhancement of around 12 dB compared to a peak of 20.4 dB. In practice such results will be complicated by the contribution of the engines and the fact that minor lobes from the wing will add and subtract from the cabin lobe at different angles, but they do give an idea of what one might expect.

Limitations of the Approach

It is noted that the above analysis is based on some major approximations. First the application of Siegels' formula, Equation 1, is based on the target being much larger than a wavelength and in many cases the parts of an aircraft that are used for scattering will be of the order of a wavelength or less. Secondly, the method of approximating the complex shape of an aircraft has its limitations. Given these approximations we should see bistatic radar theory as applied in this paper as guiding us to what might be expected rather than providing exact answers.

Total System Calculations and some Measured Results

Skolnik[1], Page 590, gives the equation for the received power for a bistatic radar system. After deleting terms for propagation losses which are negligible at VHF and UHF and converting to dB this is as follows:

$$Pr = Pt + Gt + Gr + 2*\lambda + \sigma - K - 2*Rt - 2*Rr - Lt - Lr \qquad \text{Equation 12}$$

Where Pt = Received signal in dBw
Pt = TX Power in dBw
Gt = TX Antenna Gain in dB
Gr= RX Antenna Gain in dB
λ = Wavelength in dB in metres
σ = Scattering cross section, in dB in square metres
  Back-scatter = Projected Area
  Forward-scatter = 4*π*(Projected Area Squared)/(Wavelength Squared) #
K= Constant $(4*\pi)^3$ in dB
Rt =Range from TX to target in km in dB
Rr =Range from RX to target in km in dB
Lt = TX feedline loss in dB
Lr = RX feedline loss in dB

\# From Siegel [10] at scattering angle of 180 degrees. Where the scattering angle is less than 180 degrees the effective projected area may need to be reduced – see text.

In Table 11 Equation 12 has been applied to some practical situations and compared with measured results.

RX Station	Dist' km	Frequency MHz	Power Ouput (PEP) Watts	Tx Feedline Loss dB	TX Ant' Gain dBi	RX Ant' Gain dBi	RX Feedline Loss dB	Measured Signal Level dBm	Aircraft if known	Estim'd Signal Level 747 dBm	Estim'd Signal Level 737 dBm	Difference cf 737 dB
VK7MO	530	144	15	2	2	10.4	1	-147	737	-140.9	-150	3
VK7MO	540	144	25	3	12	10.4	1	-163	737	-125.3	-135	-29
VK3KME	540	144	100	1	10	12	3	-160	737	-119.3	-128	-32
VK3UM	720	144	400	0.5	19	19.5	0	-116		-109.7	-119	3
VK3UM	720	432	400	1	24	29	0.5	-91 to -85		-99.1	-108	17 to 23
VK2ZAB	700	144	200	2.5	20	20	1	-117		-113.7	-123	6
VK2ZAB	700	432		3.5	23	24	1	-117		-111.6	-120	3
VK2ZAB	550	1296		1	22	27	1.5	-123		-115.3	-126	3
VK3AJN	550	1296		1.5	27	22	0	-123		-114.3	-125	2
VK2BE	525	1296		1	22	30	0	-111		-110	-120	9
VK2ZAB	780	144	400	0.5	15	20	0.5	-117		-115.1	-124	7
VK2ZAB	780	432	400	0.5	21	22	1	-123		-112	-121	-3
VK2ZAB	780	1296	200	1	27	27	1.5	-129		-115.1	-126	-3
VK2ZAB	713	432		2	19	22	1	-132		-121.9	-131	-2
VK2ZAB	713	1296		4	22	27	1	-136		-125	-136	-1

Table 11: Observations compared to the theory. The receiving stations made the original observations. VK3KME kindly provided observation 3, VK3UM observations 4 & 5 and VK2ZAB collected the remainder.

When investigated the around 30 dB differences in measurements by VK7MO and VK3KME proved to be due to the aircraft being out of line of site so these can be ignored. Nearly all other results are within the expected range considering possible larger aircraft (which for a 747 can result in 9 to 10 dB increases), measurement accuracy and the limitations in the methodology used to calculate the effective areas for forward scattering. McArthur's (VK3UM) 432 MHz result is much greater than can be explained by these variations. While one might be prepared to ignore this as a one-off result both McArthur and Cowan advise that there were numerous examples of such significant enhancements on 432 MHz. I accept that I cannot adequately explain McArthur's 432 MHz results.

Side Projected Areas of Aircraft

It is interesting to think about an aircraft side on as they have a much larger projected area. The projected area for a 747 comes out at about 600 square metres and much of it is less than the critical 8 metres high so will contribute to practical forward scattering on 2 metres - let us say 500 square meters. Compared to our 106 square meters for effective front-on forward scattering such an aircraft would have about 22 times or 13 dB improvement in signal level. However the fact that an aircraft is flying across the path would mean that the improvement would be for a much shorter period, perhaps just a few seconds, but it would be interesting if someone could test the theory.

Predicting Enhancement

Based on the bistatic radar theory a simple physical model has been developed to predict the possibility and time of enhancement for particular situations. It is based on the use of a map on which is plotted the aircraft flight path and the locations of the stations. A drawing pin is placed though the map from the back at the point of the transmitter location to act as a pivot. Next a piece of tracing paper is marked with a straight line. At the centre of the line is a point that represents the position of the aircraft. Two lines are drawn from this point to represent the beam-width of the forward-scatter lobe – refer Table 10. In the opposite direction to the beam-width lines a slot is cut along the first line. This slot is placed over the drawing pin. The point that represents the aircraft can now be moved so it follows the flight path. As the slot maintains alignment to the transmitter the area between the beam-width lines now shows the region in which enhancement is possible.

Conclusions

1. Bistatic radar theory, can explain significant signal enhancements due to aircraft compared to those that are calculated on the basis of normal radar reflection. On 2 meters, 70 cms and 23 cms enhancements of 20 to 30 dB can be expected.

2. Based on bistatic radar theory one can build a simple model to predict aircraft enhancement.

3. Large enhancements will only occur when the aircraft is very closely aligned between the transmitter and receiver. This means the aircraft needs to being flying along the path if it is to keep within the forward scattering lobe for a useful period. Under these conditions typical enhancements are of a few to several minutes duration and more than sufficient to complete a QSO

4. At shorter wavelengths there is a significant increase in the potential enhancement, but the alignment must be improved to gain the benefit. Given that Earth curvature prevents close alignment it is likely to be much more difficult to use aircraft enhancement at microwave frequencies.

Acknowledgements

Alf West, VK3ATX, who first suggested I look at bistatic radar theory.

Doug McArthur, VK3UM, Gordon McDonald, VK2ZAB, Ian Cowen, VK1BG, and John Patterson, VK3ATQ, who reviewed the original paper and made a number of suggestions to improve it and/or provided data.

Chris Morely, VK3KME, and numerous VK stations who assisted with experiments and provided data.

References

1. Skolnik M.I. Introduction to Radar Systems, McGraw-Hill, NY, 1962, page 591

2. McArthur D, VK3UM "Aircraft Enhancement of VHF/UHF Signals", Amateur Radio July 1985
3. McDonald G, VK2ZAB "Enhanced VHF/UHF Signal Levels due to Aircraft", Amateur Radio, October 1985
4. Harrison R, VK2ZRH (then VK2ZTB) "Aircraft Enhancement of VHF/UHF Signals", Amateur Radio, November 1985
5. McDonald G, VK2ZAB "Propagation by Reflections from Aircraft, Amateur Radio, February 1986
6. Cowan I, VK1BG "Aircraft Enhancement – Another View" Amateur Radio, March 1989
7. McDonald G, VK2ZAB "Signals reflected via Aircraft, Amateur Radio, May 1989
8. Cowen I, VK1BG "More on Aircraft Enhancement – Over to You" Amateur Radio, July 1989.
9. Barton D.K., "Radar Systems Analysis", Prentice-Hall, NJ, 1964 page 121 sec 4.4.
10. Siegel K. M. "Bistatic Radars and Forward Scattering," Proc. 1958 Natl. Conf. On Aero. Electronics, Dayton Ohio, pp 286-90.
11. Jane's "All the World's Aircraft", 1984