Aircraft Enhancement

Some Insights from Bistatic Radar Theory

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Aircraft enhancement is widely used on the east coast of Australia for VHF and UHF contacts in the 240 to 480 mile (400 to 800 km) range. Typically, for a few minutes it produces enhanced signals that are 20 to 30 dB stronger 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.

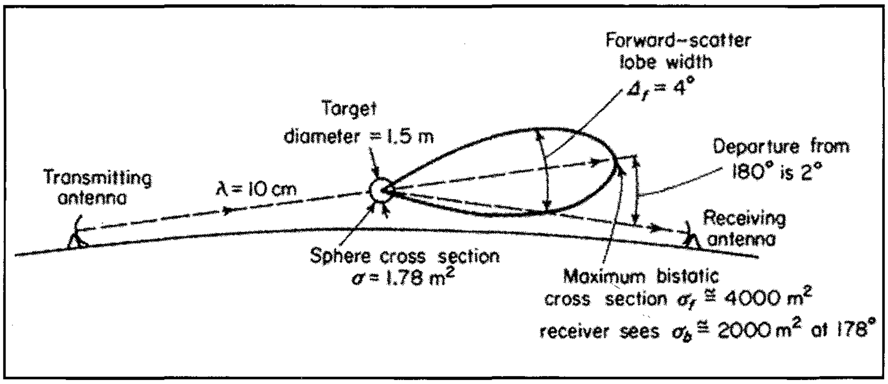

Figure 1. An example of bistatic radar where the transmitter and receiver are close to alignment. (Copied from Barton[9])

Interestingly, the phenomenon that is called *aircraft enhancement* by Australian amateurs is a manifestation of theories put forward by the French physicist Augustin Fresnel back in 1819, and the enhancement at light wavelengths is known as the Fresnel Bright Spot.

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 this example: For a sphere of radius ten times the wavelength, forward scatter is enhanced by 36 dB compared to back scatter as it applies to the more normal monostatic radar (transmitter and receiver co-located). A sphere of this size—40 meters in diameter at a wavelength of 2 meters—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 meters, the effective forward-scatter area at 2 meters is in the order of 30,000 square meters. At 70 cm the forward-scatter area can reach 240,000 square meters.

I have applied the theory to simple shapes (sphere and sections, which approximate the wings, cabin, and tail of the 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 explains significant signal enhancements, why larger enhancements might be obtained at higher frequencies, and why large enhancements only occur when the aircraft is close to the triangular alignment of the aircraft with the opposing two 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 what was 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.? Not only because it is easier, but also because it focuses on the reason for enhancement, I have chosen to try to 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 stated that 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.

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McDonald, VK2ZAB,[3,4,5] Harrison, VK2ZRH (then VK2ZTB),[6] and Cowan, VK1BG,[7,8] 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. In his May 1989 article McDonald highlighted the link to bistatic radar theory. McDonald has also advised me that Kent Britain, WA5VJB, discussed this link as early as 1986.

I will quote from the literature on bistatic radar later on in this article. First, however, some explanation of bistatic radar is in order.

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 it applies to monostatic radar. Figure 1, copied from Barton[9] (page 504), shows the situation.

The extracts below from Barton (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 back-scattering coefficient. This is because of 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."

In addition, "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 because of the relatively larger 'forward scatter' of the target, shown by Siegel[10] to be equal to:

$$\sigma_f = 4\pi A^2/(\lambda^2) \qquad \text{Equation 1}$$

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 a 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 a 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 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 meters, 70 cm, and 23 cm.

Radius of Sphere (meters)	Projected Area of Sphere (square meters)	Wavelength (dB) 2 m	70 cm	23 cm
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 into account 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 is 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 (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, it 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 (meters)	Wavelength (degrees) 2 m	70 cm	23 cm
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 is 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 kilometers because of Earth curvature and aircraft height, and thus this limits the enhancement that 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:

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

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 kilometers 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 on 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 beamwidth at an angle of departure of 7 degrees.

Wavelength	2 m	70 cm	23 cm
Radius of Sphere (meters)	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 meters in radius at 2 meters and substantially less at 70 cm and 23 cm. While the cabins of aircraft will be useful at 2 meters (even a 747 is just less than 4 meters 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 times wider than their height. Returning to Equation 2, which determines the beamwidth, 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 beamwidth 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 in square meters for various sections 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 meters in 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 meters) and heights in brackets (meters) 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 were no angle of departure.

Aircraft and Projected Area (square meters)	Potential Enhancement (dB) 2 m	70 cm	23 cm
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 beamwidth of the larger vertical sections of the aircraft (i.e., 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 beamwidth of 7 degrees and thus be useful on a typical aircraft enhancement contact.

Wavelength	**2 m**	**70 cm**	**23 cm**
Section Height (meters)	8.2	2.9	0.9

Table 7. Maximum height 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 3-dB 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 meters the tail is too long to be useful and the cabin is on the margin (i.e., 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 meters. At 70 cm only the wings are useful, giving an effective projected area of 64 square meters. At 23 cm much of the front wing is too large, and 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 2 meters the tail must be deleted, as it adds to the cabin, like stacking two vertical antennas; 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 meters. 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 meters.

The data for a 747 and a 737 are summarized in Table 8.

	Effective Projected Area (square meters)		
Aircraft	**2 m**	**70 cm**	**23 cm**
747	106	64	20
737	37	24	6

Table 8. Effective projected areas for a 747 and a 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 (i.e., that for a normal monostatic radar), noting that the effective forward-scatter area is somewhat less than the projected area as shown in 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.

	Enhancement (dB)		
Aircraft	**2 m**	**70 cm**	**23 cm**
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.

A value of 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 MHz, consistent with a statement by McArthur in relation to 432 MHz: "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 beamwidth in the horizontal plane, as this, combined with the speed with which the aircraft passes through alignment, controls the duration of enhancement. The horizontal beamwidth 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 beamwidth in the horizontal plane based on a wingspan for a 747 of 64 meters and for a 737 of 28 meters. We also look at the cabin sections 747 (6.8 meters) and 737 (4 meters), as these can contribute a wider beamwidth, although lower enhancement lobe at 2 meters.

	Wavelength (degrees)		
Aircraft Section	**2 m**	**70 cm**	**23 cm**
747 wing 64 meters	1.8	0.6	0.2
737 wing 28 meters	4.1	1.4	0.5
747 cabin 6.8 meters	17	—	—
737 cabin 4 meters	29	—	—

Table 10. Beamwidth 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 usable at the higher frequency, then the reduction should be in proportion to the wavelength. This conclusion is at least partly supported by McArthur, 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 2 meters the cabin can contribute to the enhancement, and it will provide a wider horizontal beamwidth, 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 (i.e., about 20 square meters). 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 2 meters, 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. However, 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 Siegel's 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 on the order of a wavelength or less. Second, 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 (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:

$$P_r = P_t + G_t + G_r + 2*\lambda + \sigma - K - 2*R_t - 2*R_r - L_t - L_r \qquad \text{Equation 12}$$

where:

P_r = Received signal in dBw
P_t = TX power in dBw
G_t = TX antenna gain in dB
G_r = RX antenna gain in dB
λ = Wavelength in dB in meters
σ = Scattering cross section, in dB in square meters
Back scatter = Projected Area
Forward scatter =
4*π*(Projected Area Squared)/(Wavelength Squared) †
K= Constant $(4*\pi)^3$ in dB
R_t =Range from TX to target in km in dB
R_r =Range from RX to target in km in dB
L_t = TX feedline loss in dB
L_r = RX feedline loss in dB

(†From Siegel, 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.

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 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 aircrafts side-on, as they have a much larger projected area. The projected area for a 747 comes out to about 600 square meters, and much of it is less than the critical 8 meters high, so it will contribute to practical forward scattering on 2 meters—let's 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 means that the improvement would be for a much shorter period, perhaps just a few seconds. However, 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

RX Station	Dist. (km)	Freq. (MHz)	Power Output PEP (watts)	TX Feedline Loss (dB)	TX Antenna Gain (dBi)	RX Antenna Gain (dBi)	RX Feedline Loss (dB)	Measured Signal Level (dBm)	Aircraft (if known)	Estimated Signal Level 747 (dBm)	Estimated 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 and 5; and VK2ZAB collected the remainder.

a map on which the aircraft flight path and the locations of the stations are plotted. A drawing pin is placed through 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 center of the line is a point that represents the position of the aircraft. Two lines are drawn from this point to represent the beamwidth of the forward-scatter lobe (refer to Table 10). In the opposite direction to the beamwidth lines a slot is cut along the first line. This slot is placed over the drawing pin. The point that represents the aircraft now can be moved so it follows the flight path. As the slot maintains alignment to the transmitter, the area between the beamwidth lines now shows the region in which enhancement is possible.

Conclusions

The following conclusions are made from the information presented in this paper:

1. Bistatic radar theory can explain significant signal enhancements because of aircraft, compared to those which are calculated on the basis of normal radar reflection. On 2 meters, 70 cm, and 23 cm 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 in 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.

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