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WIND TUNNEL EXPERIMENTS TO ASSESS THE EFFECT OF BACK-MOUNTED RADIO TRANSMITTERS ON BIRD BODY DRAG

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SUMMARY

The aerodynamic drag of bird bodies was measured in a wind tunnel, with and without back-mounted dummy radio transmitters. Flight performance estimates indicate that the drag of a large transmitter can cause a substantial reduction of a migrant's range, that is, the distance it can cover in non-stop flight. The drag of the transmitter can be reduced by arranging the components in an elongated shape, so minimizing the frontal area. The addition of a rounded fairing to the front end, and a pointed fairing behind, was found to reduce the drag of the transmitter by about one-third, as compared with an unfaired rectangular box.

INTRODUCTION

Affixing radio transmitters has become widespread for the study of habitat use, mortality, migration, home range and physiology (Amlaner & Macdonald, 1980). Some effects have been documented of radio-marking on physical condition, behaviour and mortality of birds (Greenwood & Sargeant, 1973; Gilmer, Ball, Cowardin & Riechmann, 1974). However, there are few empirical data about the aerodynamic impact of back-mounted radio transmitters on birds.

A radio transmitter affects a bird's flight performance in two direct ways, by increasing its weight and by increasing the drag of its body (Pennycuick & Fuller, 1988). The added drag may be negligible for a small transmitter that can be preened under the contour feathers. However, additional drag might influence flight when large transmitters are used, such as those designed to be tracked by satellite (Fuller *et al.* 1984). With present technology, satellite-compatible transmitters are large packages (160 g), whose added mass or drag might impair flight performance, even of a large bird, and affect its survival or reproductive success.

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We are particularly concerned here with the effect of radio marking on the flight range of long-distance migrants. Existing flight models, such as that of Pennycuick (1975), supply a basis for estimating the effect on range, if the magnitudes of the added mass and drag are known. At present, the mass is known for each transmitter, but the magnitude of the added drag is not. Experimental work on aircraft fuselages, summarized by von Mises (1945), shows that the drag of a streamlined body, with a secondary smaller body attached to it, is generally greater than the sum of the drag measured on each of the two bodies separately. It is not sufficient, therefore, to measure the drag of transmitters in isolation. The increment of drag caused by the transmitter has to be estimated by measuring the drag of a bird body with and without a transmitter. Our objectives were (1) to determine the effect of back-mounted radio transmitters on the aerodynamic drag of bird bodies, (2) to test fairings intended to reduce the drag of the transmitter, and (3) to estimate the effect of faired and unfaired satellite-trackable transmitters on migration range.

MATERIALS AND METHODS

The experiments were performed in the Glenn L. Martin Wind Tunnel at the University of Maryland, using the same bird bodies and mounting and testing procedures as described by Pennycuick, Obrecht & Fuller (1988). The dummy transmitters were shaped from balsa wood, and painted with glossy white enamel. A strip of Velcro fastening material was glued to the base of each transmitter, so that it could be easily attached to a mating Velcro strip, glued with 5-min epoxy resin to the back of each specimen. The Velcro strip on the bird was positioned approximately above the bird's centre of gravity. Three sizes and four styles (Fig. 1) of transmitter were tested. Style A was a rectangular box, while styles B, C and D had various types of streamlined fairings, surrounding the same basic box. In style B, the box was enclosed in a blister fairing, with increased cross-sectional area. In styles C and D, the cross-section of the box was unchanged, but a rounded fairing was added to the upstream end, and a pointed fairing to the downstream end. In style C these end

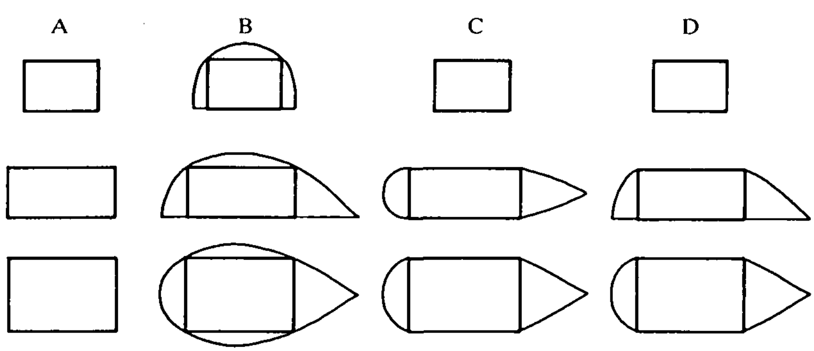

Fig. 1. The four styles of transmitter tested, shown in front view (upper), side view (middle) and top view (lower). The anterior end of the transmitter faces left in the side and top views.

fairings were symmetrical as seen in side view, whereas in style D they were faired down on to the bird's back. Style C transmitters were tested with and without whip antennae that were either 1·5 mm o.d. × 326 mm uncoated aircraft cable, or 3·0 mm o.d. × 165 mm vinyl-coated aircraft cable. They were attached at the two-thirds chord point on the top of the transmitter, inclined backwards at 45°.

The three sizes of dummy transmitters corresponded to functional transmitters (Table 1). The smallest dummy (size 1) represented a conventional 30 g transmitter, commonly used on ducks. Size 2 represented a very large (80 g) conventional transmitter, or a 'second-generation' satellite transmitter (still under development) that could be used on geese. Size 3 represented a 160 g 'first-generation' satellite-trackable transmitter, currently being field-tested on eagles and swans (Strikwerda *et al.* 1986). Measurements were performed with the dummy radio transmitters attached to the frozen, wingless bodies of a bald eagle (*Haliaeetus leucocephalus*), a tundra swan (*Cygnus columbianus*), a snow goose (*Chen caerulescens*) and a mallard (*Anas platyrhynchos*), prepared and mounted as previously described (Pennycuick *et al.* 1988).

In each series of measurements, a bird body was mounted in the tunnel, and its drag was measured without a transmitter, and then with each of several different dummy transmitters. The feathers were smoothed down by hand before each measurement. The drag of the body without a transmitter was subtracted from each of the measurements with a transmitter, to give an incremental drag (ΔD) for that transmitter. This was converted into an incremental effective flat-plate area (ΔS) by the formula:

$$\Delta S = \Delta D/Q\,, \tag{1}$$

where Q is the dynamic pressure, given by:

$$Q = \rho V^2/2\,. \tag{2}$$

ρ is the air density and V is the air speed. The incremental effective flat-plate area, so determined, can be divided by the actual frontal area of the transmitter (S_r) to give a drag coefficient (C_D) for the transmitter, thus:

$$C_D = \Delta S/S_r\,. \tag{3}$$

In several of the experiments, drops of dark blue ink were applied to the surface of the transmitter, to show where the boundary layer was separated, and the direction of flow in areas where it was attached. Finally, we experimented with truncation and turbulator strips on transmitter size 2, style B. The turbulator strip was a 4 mm wide strip of masking tape across the top of the dummy near the one-third chord point.

Table 1. *Dimensions of transmitter boxes*

Size	Length (mm)	Width (mm)	Height (mm)	Frontal area (mm^2)
1	57·2	20·3	19·7	400
2	85·7	40·0	31·8	1270
3	81·9	55·9	38·1	2130

The same transmitter was also tested in a truncated form, by cutting 3·5 cm from the downstream end, perpendicular to the longitudinal axis.

RESULTS

Our results (Table 2) are based on observations for which the dynamic pressure was in the range 345–690 Pa. Higher dynamic pressures caused excessive disturbance of the feathers (see Pennycuick *et al.* 1988), whereas at values below 300 Pa, the increments of drag caused by the transmitters were too small to be discriminated by the measurement system. As we were interested primarily in the differences between the various transmitter styles, we combined the results from different bird bodies to give a mean value of the incremental effective flat-plate area for each style and size of transmitter.

The drag measurements for size 1 were too variable to be used, because the increments of drag were too small to be measured with our equipment. The drag coefficient estimates for sizes 2 and 3 in style A (rectangular box) had values of 0·72 and 0·49, respectively, whereas all the other styles showed values ranging from 0·29 to 0·46. When the values for sizes 2 and 3 were pooled (bottom line of Table 2), the resulting values suggested that the drag coefficient was about 0·6 for style A, and about 0·4 for the other styles. The implication is that the drag of the transmitter can be reduced by a factor of about two-thirds by the addition of simple end fairings as in styles C and D. Style B also shows a reduced drag *coefficient*, but it has more cross-sectional area than style A. Consequently, the incremental drag is much the same for style B as for style A. The addition of a turbulator strip, and truncation of the rear end of transmitter size 2, style B, did not produce any measurable change in the drag.

Table 2. *Incremental flat-plate area (ΔS in mm^2) and drag coefficient (C_D) of transmitters*

	Style	A	B	C	C+antenna	D
Size 1	ΔS	0·1 (3)	2·8 (1)	1·0 (3)	1·2 (2)	3·6 (1)
	S.D.	0·6		0·9	0·8	
	C_D	0·03	0·45	0·28		1·0
Size 2	ΔS	9·2 (5)	8·6 (3)	5·3 (6)	7·7 (5)	4·8 (1)
	S.D.	3·5	1·8	1·6	2·2	
	C_D	0·72	0·40	0·42	0·46	0·38
Size 3	ΔS	10·5 (4)	14·3 (1)	6·2 (5)	8·6 (4)	8·7 (1)
	S.D.	4·8		3·6	3·3	
	C_D	0·49	0·44	0·29	0·34	0·41
Sizes 2 and 3: Mean C_D		0·61	0·42	0·36	0·40	0·40

The number of observations on which each estimate of ΔS is based is shown in brackets, with the standard deviation where applicable.

Fig. 2 is a photograph of transmitter 2C attached to a mallard body, with ink spots to reveal the pattern of flow. Some of the ink spots have run downwards a short distance before the wind was turned on. Then, the ink has run in the downstream direction on the top, sides and rear of this shape, showing the boundary layer was attached. However ink flow patterns on transmitter 3D on the tundra swan indicated a point of separation and reverse flow at the top rear, where the aft fairing joined the transmitter block.

DISCUSSION

We can now estimate the probable effect of the larger transmitters on one particular aspect of flight performance, a migrant's range, that is the distance it can fly until all of its stored fat is used up. A method for estimating migration range has been published by Pennycuick (1975). This theory is an updated version of an earlier theory (Pennycuick, 1969), incorporating a number of amendments proposed by Tucker (1973). It may be noted that earlier versions of the theory contained some errors, including a method for calculating profile power introduced by Tucker (1973), which greatly exaggerates the U shape of the power curve. Although this was rectified in the version of Pennycuick (1975), curves embodying this highly misleading feature have appeared in some recent publications, including Peters (1983) and Caccamise & Hedin (1985).

We implemented the power curve of Pennycuick (1975) in the form of a BASIC program on a Commodore Amiga computer. The only modification we introduced was to calculate the effective flat-plate area of the body according to the most recent data (Pennycuick *et al.* 1988). The program in this form predicted, to within 10%, the recently published results of Rothe, Biesel & Nachtigall (1987) on the oxygen consumption of pigeons in prolonged flight in a wind tunnel. The transmitter was represented in the program by adding its mass to the body mass, and by adding an increment of effective flat-plate area, taken from the results above, to the estimated flat-plate area of the bird's body.

As an example we chose a snow goose (*Chen caerulescens*) with a mass of 3·24 kg at take-off, and a wing span of 1·6 m. We assumed that 20% of the initial body mass (0·65 kg) consisted of fat, to be consumed in the course of the flight. These figures are representative of the premigratory mass and fat content reported for males of this species by Gauthier, Bedard, Huot & Bedard (1984). We estimated the distance that the bird could fly, using up all its fat, first unloaded, and then with transmitters 2A, 2C, 3A and 3C. The mass of the size 3 transmitters was assumed to be 160 g, and that of the size 2 transmitters 80 g. In Fig. 3, the calculated power curves for transmitters 3A and 3C are compared with the unloaded power curve. The added weight is mainly responsible for increasing the power at low speeds, while the added drag causes the increase at high speeds. The curves for transmitters 3A and 3C, which differ only in that 3A has more drag, diverge at higher flight speeds. The extra drag causes a slight decrease in the maximum range speed and an increase in the power required to fly at that speed.

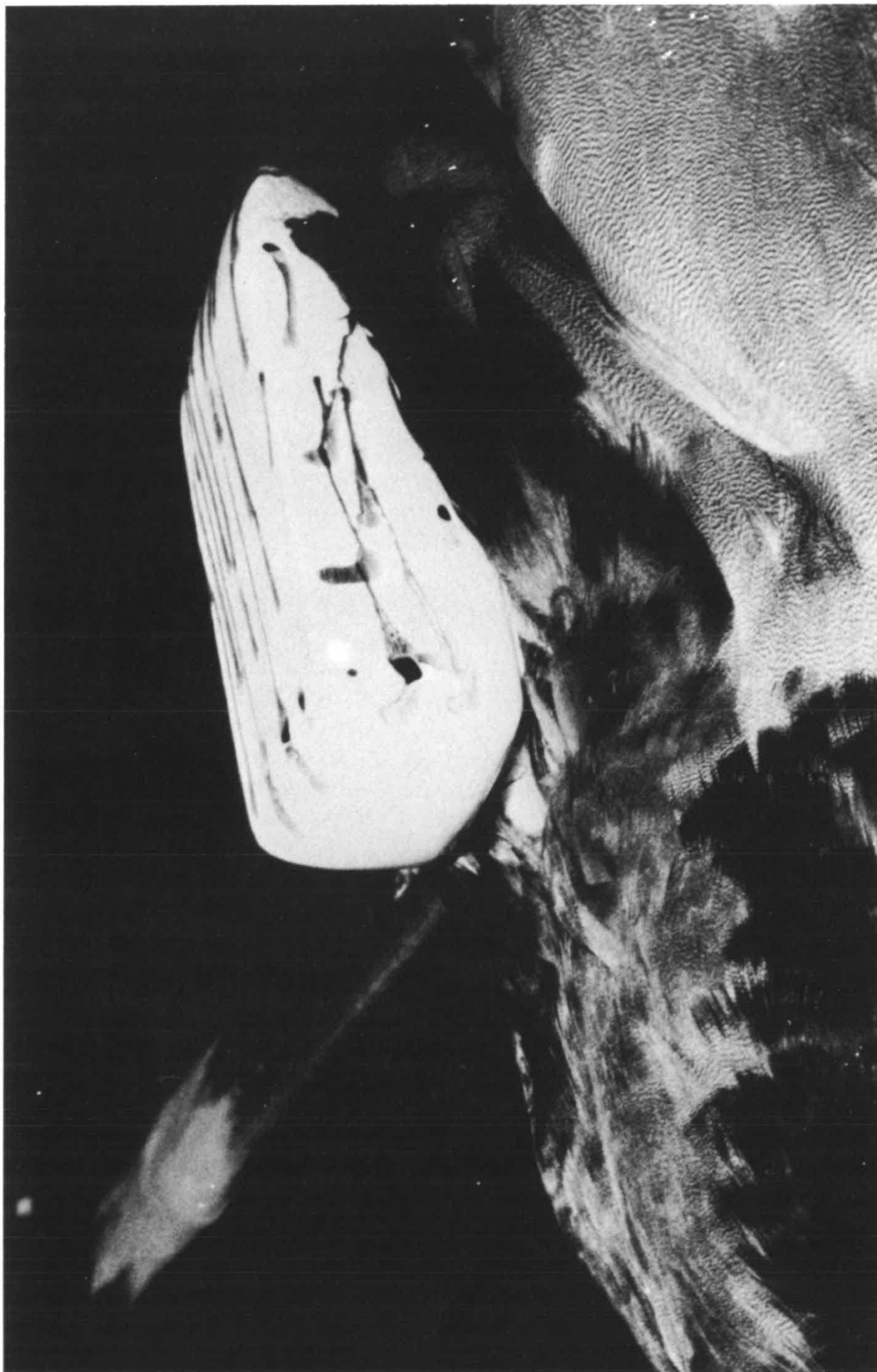

Fig. 2. Transmitter 2C attached to a mallard body. Five rows of ink drops were applied to the transmitter before testing. The drops have been spread into lines by the wind, along the direction of flow, showing that the boundary layer was attached over nearly the whole surface of the transmitter.

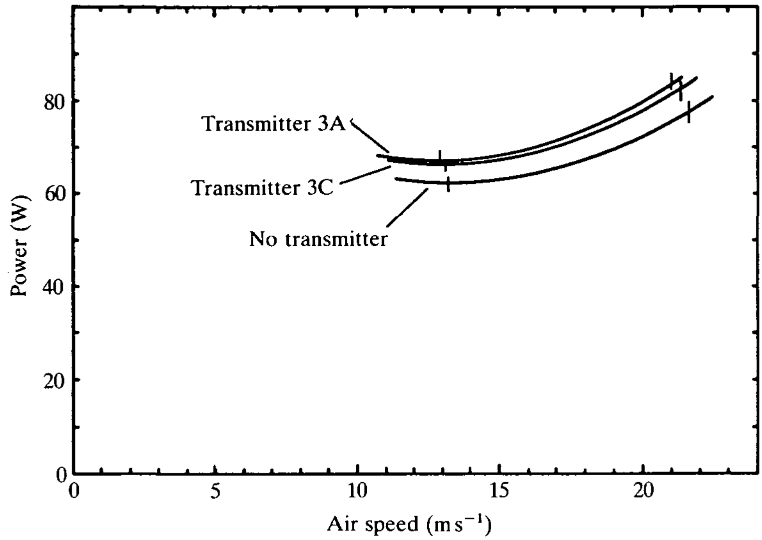

Fig. 3. Power curves calculated by the method of Pennycuick (1975) for a snow goose without a transmitter, and with transmitters 3A and 3C. The short vertical bars mark the minimum power speed (left) and maximum range speed (right) on each curve.

The effect of different transmitters on the estimated range (Table 3) was calculated on the assumption that, with the transmitter in place, the flight muscles are able to supply the additional power needed to fly at the maximum range speed. The 'range penalty' is the difference in the range with and without the transmitter. If the bird were obliged to fly more slowly than its maximum range speed, because of the effect of the transmitter, then the range penalty would be greater than indicated in Table 3. Some further possible effects are considered hypothetically by Pennycuick & Fuller (1988). The estimated range penalties, caused by the test transmitters, are quite substantial, even under the relatively optimistic assumptions underlying Table 3. The small reduction of drag achieved by adding end fairings (changing style A to style C), results in 41 km of additional range for a size 2 transmitter and 61 km for size 3.

Table 3. *Calculated ranges for snow goose with various transmitters*

Transmitter	Mass (g)	ΔS (mm^2)	Range (km)	Penalty (km)	Penalty (%)
None			1845		
2 (dragless)	80		1798	47	2·5
2A	80	762	1663	182	9·9
2C	80	508	1704	141	7·6
3 (dragless)	160		1752	93	5·0
3A	160	1280	1546	299	16·2
3C	160	852	1607	238	12·9

The same transmitters would produce a smaller range penalty on a larger bird than the snow goose, and a greater one on a smaller bird. The size of the effect depends mostly on the ratio of the transmitter's effective flat-plate area to that of the bird. The transmitter's flat-plate area can be minimized by using an elongated basic shape (to minimize the frontal area), and by adding end fairings if the transmitter projects above the back feathers. Table 3 includes estimates for hypothetical transmitters that have mass and weight, but do not cause any increase in body drag. Comparing these with the real transmitters shows that most of the range penalty is due to the added drag of the transmitters, rather than to the added weight. However, it would be imprudent to apply this conclusion too generally, since not all radiotracking is concerned with migrants. The notion of a range penalty might have little significance for, say, a raptor feeding nestlings. In such a case, the weight of the radio might be more important than the drag.

Best transmitter shape

If we confine our attention to the problems of migration, then the estimates in Table 3 suggest that it is worthwhile to take any practicable measures to reduce the drag of the transmitter. Our results (Table 2) indicate that the best way to reduce the drag of a rectangular box (style A) is to fit end fairings, as in styles C or D, without increasing the frontal area. Style C is preferred to style D, because there is less contact area with the bird's back, and less disturbance to the feathers. The fairings can be made from some low-density material such as expanded polystyrene, and glued to the ends of the transmitter. It may even be possible to avoid the need for fairings, by arranging the components so that the transmitter is shaped like style C in the first place. The elongated shape of the size 2 second-generation satellite transmitter is better than the wider shape of the size 3 transmitter, because it has less frontal area in relation to its volume.

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REFERENCES

AMLANER, C. J. & MACDONALD, D. W. (1980). *A Handbook on Biotelemetry and Radio Tracking.* Oxford: Pergamon Press.

CACCAMISE, A. F. & HEDIN, R. S. (1985). An aerodynamic basis for selecting transmitter loads in birds. *Wilson Bull.* **97**, 306–318.

FULLER, M. R., LEVANON, N., STRIKWERDA, T. E., SEEGAR, W. S., WALL, J., BLACK, H. R., WARD, F. P., HOUSEY, P. W. & PARTELOW, J. (1984). Feasibility of a bird-borne transmitter for tracking via satellite. In *Proceedings of the 8th International Symposium on Biotelemetry* (ed. H. P. Kimmich & H.-J. Klewe), pp. 375–378. Nijmegen, Netherlands: International Society for Biotelemetry.

GAUTHIER, G., BEDARD, J., HUOT, J. & BEDARD, Y. (1984). Spring accumulation of fat by greater snow geese in two staging habitats. *Condor* **86**, 192–199.

GILMER, D. S., BALL, I. J., COWARDIN, L. M. & RIECHMANN, J. H. (1974). Effects of radio packages on wild ducks. *J. Wildl. Mgmt* **38**, 243–252.

GREENWOOD, R. J. & SARGEANT, A. B. (1973). Influence of radio packs on captive mallards and blue-winged teal. *J. Wildl. Mgmt* **37**, 3–9.

PENNYCUICK, C. J. (1969). The mechanics of bird migration. *Ibis* **111**, 525–556.

PENNYCUICK, C. J. (1975). Mechanics of flight. In *Avian Biology*, vol. 5 (ed. D. S. Farner & J. R. King), pp. 1–75. New York: Academic Press.

PENNYCUICK, C. J. & FULLER, M. R. (1988). Consideration of effects of radio transmitters on bird flight. *Proceedings of the 9th International Symposium on Biotelemetry* (ed. H. P. Kimmich & H.-J. Klewe). Nijmegen, Netherlands: International Society for Biotelemetry (in press).

PENNYCUICK, C. J., OBRECHT, H. H. & FULLER, M. R. (1988). Empirical estimates of body drag of large waterfowl and raptors. *J. exp. Biol.* **135**, 253–264.

PETERS, R. H. (1983). *The Ecological Implications of Body Size.* Cambridge: Cambridge University Press.

ROTHE, H.-J., BIESEL, W. & NACHTIGALL, W. (1987). Pigeon flight in a wind tunnel. II. Gas exchange and power requirements. *J. comp. Physiol.* B **157**, 99–109.

STRIKWERDA, T. E., FULLER, M. R., SEEGAR, W. S., HOWEY, P. W. & BLACK, H. D. (1986). Bird-borne satellite transmitter and location program. *Johns Hopkins appl. Phys. Lab. Techn. Digest* **7**, 203–205.

TUCKER, V. A. (1973). Bird metabolism during flight: evaluation of a theory. *J. exp. Biol.* **58**, 689–709.

VON MISES, R. (1945). *Theory of Flight.* New York: Dover.