Radar Characteristics of Birds in Flight

Radar tracking of known single birds indicates a characteristic radar "signature."

Thomas G. Konrad, John J. Hicks, Ella B. Dobson

The identification of the so-called "dot angels"—radar returns from unknown point targets—has been, and continues to be, a subject of much study and conjecture. There is no doubt that radar returns from birds and insects account for many of the dot angels. Radar detection of birds dates from the mid-1940's (*1*), and radar has since been used extensively in the study of bird flight, roosting, feeding, and migration patterns (*2*, *3*). Where radar is used in this connection, the identification of targets is often made visually from the ground or from an aircraft. In other cases, however, the radar operator is unable to identify visually the source of the radar returns. The identification must then be based on the number of targets and on the characteristics of the target track as compared with possible aircraft or insect tracks and with the speed and direction of the winds. Attempts have been made to catalog various physical characteristics and habits of birds—such as their length and cross-sectional area, the heights and speeds of their flight, and diurnal and seasonal variations in their movements—and to compare these characteristics with those of the dot angels (*3*, *4*). On the basis of this somewhat circumstantial evidence, it is concluded that many dot angels are radar returns from birds.

Birds constitute a significant hazard to aircraft in flight. Studies are at present under way to investigate the possibility of using ground-based radar to detect and track bird movements. If such tracking proved feasible, flight controllers could then warn pilots of hazardous areas. Such a system would enable pilots to detour around migrating flocks of birds, much as they now avoid thunderstorms.

Very little information, however, is available concerning the magnitude and the character of the returned radar signal from a known bird target (*5–8*)—information which would allow the radar operator to make a direct, real-time identification of a dot angel as a bird in terms of a radar "signature."

A number of experiments were performed at the Joint Air Force–NASA (JAFNA) radar facility at Wallops Island, Virginia, wherein birds of known species were ejected individually from an aircraft and the returned radar signal and the position of the single-bird target were recorded. The primary purpose of the experiments, and of the analysis reported here, was not to study birds as such but to test the view that birds were the source of some of the dot angels and to determine whether the radar return from known, single birds in flight contained any recognizable radar signature by which the birds could be identified.

Test Description

Briefly stated, the JAFNA radar complex consists of three radars—X-band (3.2 centimeters), S-band (10.2 centimeters), and UHF (71.5 centimeters). The S-band and UHF radars have parabolic dish antennas of 60-foot (18-meter) diameter, producing 0.48- and 2.9-degree beam widths, respectively. The X-band antenna is the center 34-foot-diameter portion of the UHF antenna and produces a beam 0.21 degree wide. The S-band radar is a monopulse tracking radar, to which the X-band and UHF antennas are slaved. Peak transmitter power at X, S, and UHF frequencies is 0.9, 3.0, and 6.0 megawatts, respectively. All systems transmit and receive vertical polarization and operate at a pulse-repetition rate of 320 pulses per second. The UHF system can, in addition, receive the cross-polarized component or horizontal polarization.

Three bird species were used in the experiment: the boat-tailed grackle (*Cassidix mexicanus*), the common house or English sparrow (*Passer domesticus*), and the homing pigeon (*Columba livia*). Five individual birds were tracked: two boat-tailed grackles, two sparrows, and one pigeon.

The technique used to track individual birds was as follows. The birds were placed in individual containers and taken by airplane to an altitude of between 5500 and 6000 feet. The aircraft then flew a constant-altitude, outbound radial path from the radar. The drop zone was from 8 to 10 nautical miles (15 to 18½ kilometers) east of the radar, over water. During the outbound run the radars were automatically tracking the airplane. If the region around the aircraft was observed (on the A-scope) to be free of other radar targets, a single bird was ejected from the plane. Automatic tracking of the aircraft was adopted at the instant the bird was ejected, and the radar beam was fixed on the drop zone. The aircraft continued on its radial course, leaving the bird in the radar beam. The separation of the radar return from the bird from the stronger return from the aircraft was obvious when viewed on an A-scope. When the two targets had separated sufficiently, the radars were reset for automatic tracking of the bird. The aircraft continued on its outbound run for several miles and then orbited to avoid possible contamination of the radar return from the bird by radar return from the aircraft.

Each bird was automatically tracked for periods up to 5 minutes, during which time the radar return at all three wavelengths and the position data (azimuth, elevation, and range) were recorded. These data were recorded on a high-speed printer at a rate of one point per second throughout the tracking period, with bursts of recording speed of 20 points per second for 15- to 30-second intervals. The returned signal level on each radar was also recorded on an X–Y plotter as a function of time.

The authors are affiliated with the Johns Hopkins University's Applied Physics Laboratory, Silver Spring, Maryland.

Experimental Results

The power received, P_r, by a radar from a point target located at some distance, r, from a radar is given in standard radar texts (*9*) as:

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 r^4} \sigma$$

where P_t is the transmitted power, G is the one-way antenna gain, λ is the radar wavelength, and σ is the radar cross section of the target. Of the various terms in the radar equation, only σ is a characteristic of the target; it is a measure of the target's efficiency for scattering radiation back to its source. That is,

σ = [(power reflected toward source)/ (unit solid angle)] ÷ (incident power density)

In other words, σ represents the size of a target as "seen" by the radar. In general, the cross section is a function of the polarization and frequency of the incident radiation and the shape and dielectric constant of the target. For simple, well-defined targets such as metal spheres, the cross section may be theoretically determined through solution of Maxwell's equations subject to appropriate boundary conditions. For complicated targets, the cross section is usually determined experimentally. In any case, the radar cross section is the characterizing parameter and may be examined for distinguishing features peculiar to a given target or class of targets.

Typical examples of the returned radar signal, in terms of radar cross section, for a grackle, a sparrow, and a pigeon, as measured on the S-band radar, are shown in Fig. 1. During the time interval shown for each target, the range did not change appreciably, so a single cross section scale may be used. Note the large fluctuations in the received signal. At times the maximum and minimum intensities differ by more than two orders of magnitude. The mean radar cross section is generally related to the size and shape of the bird. The fluctuations in the radar return are a result of changes in the orientation of the body relative to the polarization of the incident radiation —wing motion, head motion, and so on—during the flight. Other investigators have noted these effects. Houghton and Edwards (*5, 6*) measured the radar cross section of several bird species as a function of aspect angle. The wings were folded in all cases, but still the cross section varied typically by from one to two orders of magnitude with changes in aspect angle. Blacksmith (*8*) found that the returned signal from a standing duck was very sensitive to the position of the duck's head and neck. The radar return from a turkey buzzard in flight fluctuated between 25 and 250 square centimeters, as reported by LaGrone *et al.* (*7*).

Thus a bird in flight is a complicated target which produces a highly fluctuating radar return. As such, the radar cross section cannot be described by a single value and is considered here in statistical terms—that is, in terms of the mean, the median, the probability distribution, and the fluctuation spectrum of the cross section.

The radar cross section for each bird target at each radar wavelength was

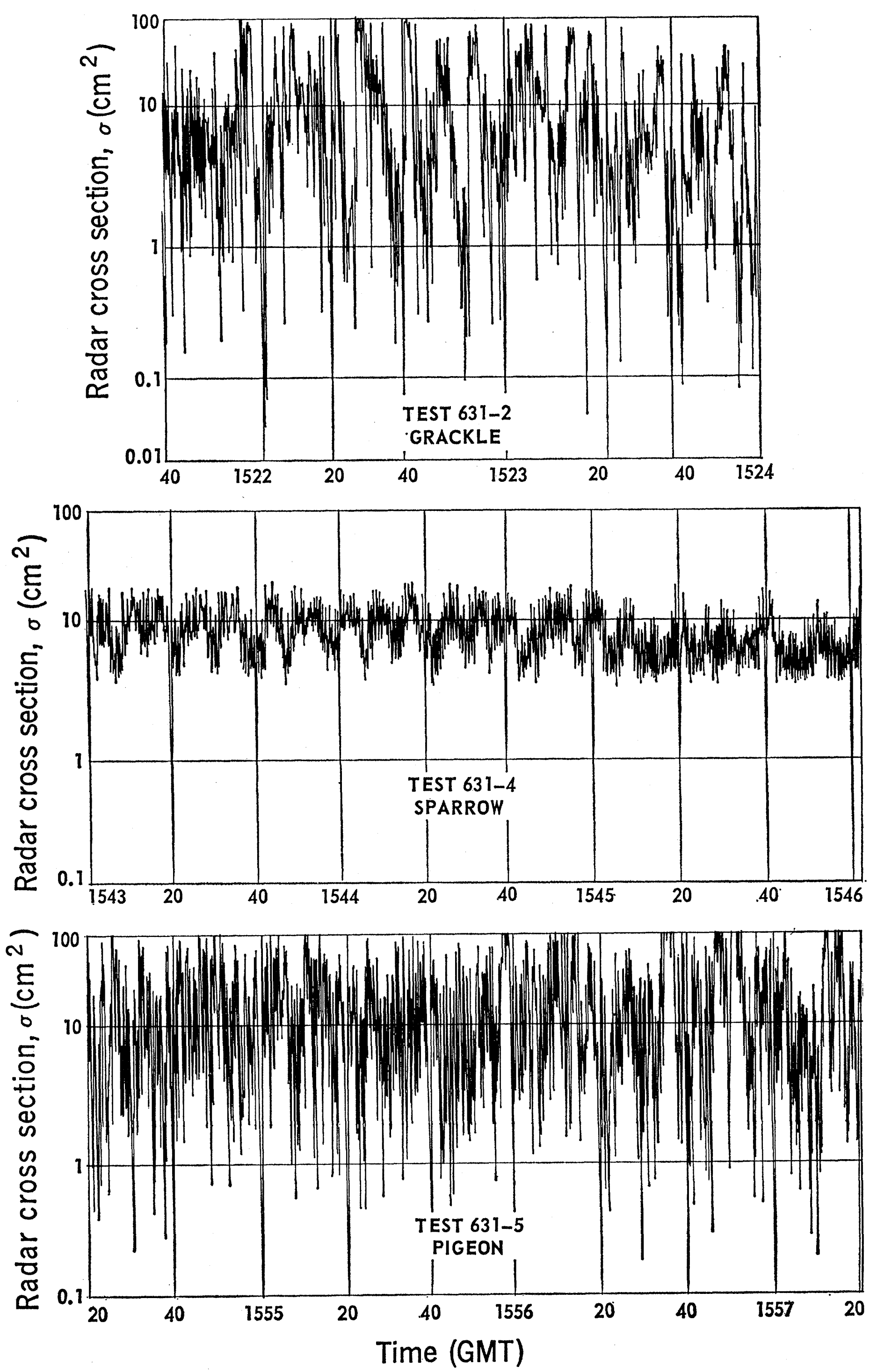


Fig. 1. Typical time history of radar cross section for a single bird, at S-band wavelengths.

Table 1. Summary of bird cross-section data.

Radar band	Points (at 1 point/sec)	Mean radar cross section (cm^2)	Median radar cross section (cm^2)	Root-mean-square fluctuations in cross section (cm^2)	Mean-to-median ratio, ρ
			Grackle		
X	230	16	6.5	24	2.4
S	230	27	13	31	2.2
UHF-VV*	230	0.73	0.58	0.6	1.3
UHF-VH†	230	0.37	0.15	0.7	
			Grackle		
X	116	15	7.2	21	2.1
S	116	23	11	32	2.2
UHF-VV	116	0.41	0.32	0.5	1.3
UHF-VH	116	0.03	0.015	0.04	
			Sparrow		
X	129	1.9	1.0	2	1.9
S	129	15	11	11	1.4
UHF-VV	129	0.025	0.02	0.02	1.3
UHF-VH	129				
			Sparrow		
X	233	1.3	0.60	2	2.2
S	233	12	11	5	1.1
UHF-VV	233	0.020	0.02	0.01	1.1
UHF-VH	233				
			Pigeon		
X	160	15	6.4	28	2.3
S	160	80	32	140	2.5
UHF-VV	160	11	8.0	7.0	1.3
UHF-VH	160	1.2	0.7	1.4	

* VV, Transmit vertical polarization and receive vertical polarization. † VH, Transmit vertical polarization and receive cross-polarized or horizontal component.

calculated from data recorded at a rate of one point per second throughout the flight. The arithmetical mean and median cross sections and the root mean squares of the fluctuations in cross section are shown in Table 1, along with the number of points used in each calculation. The mean and median cross sections for a bird of a given size do not exhibit a simple wavelength or size dependence. This result might well be expected in view of the size and shape of the bird relative to the radar wavelengths used and the nonhomogeneous nature of the bird's dielectric constant. Blacksmith (*8*) also noted a "resonant" behavior at ultrahigh frequency (400 megacycles), where the radar cross section of a small duck was nearly twice that of a larger duck. Measurements of the dielectric constant for birds are nonexistent. However, as an example of the complex dielectric constant, ϵ_c, characteristic of animal tissue, we can use Von Hippel's measurements for steak (*10*):

$$\text{X-band: } \epsilon_c = 31 - i12$$
$$\text{S-band: } \epsilon_c = 40 - i12$$
$$\text{UHF: } \epsilon_c = 49 - i34$$

Houghton (*6*) found that the dielectric constant of dry, tightly packed, and "correctly" oriented feathers measured $1.25 - i0$ at S-band wavelengths and $1.34 - i0$ at X-band wavelengths.

In light of the above, it was not considered fruitful to pursue the prediction of radar cross section on the basis of existing scattering theory.

A summary of the radar cross section data for single birds of known species, as measured by other investigators (*5–8*), is shown in Table 2, for purposes of comparison. The radar cross sections are presumed to be mean cross sections. The measurements by Edwards, Houghton, and Blacksmith (*5, 6, 8*) are for birds in a static or fixed position. The data for the turkey buzzard (*7*) were obtained by LaGrone *et al.* while the bird was in flight, but they report only the limits of the fluctuations in cross section.

If it can be established that the probability distributions of the radar cross sections of birds are characteristically different from those of other target classes, one could use this fact for identifying dot echoes as birds. That is, the radar cross section probability distribution could be considered part of a radar signature.

The probability density, $p(\sigma)$, and cumulative probability, $P(\sigma)$, distributions of the radar cross section were calculated from data obtained at a rate of one point per second. The distributions calculated from the data were then compared with known distributions such as the Gaussian, Rayleigh, and exponential. Typically, the calculated distributions are characterized by large dynamic ranges and variances and do not follow or fit any of these known distributions. The data, however, do appear to follow a log-normal distribution. The cumulative probability distributions of the radar cross section are shown in Figs. 2, 3, and 4. The data for the duck at a frequency of 400 megacycles (*8*) are also included in Fig. 4. The near-linearity of the plotted data strongly suggests that the radar-cross-section distribution for a single bird in flight is log-normal. Note that at X-band and UHF wavelengths the slope of the curves for all birds, regardless of bird size, is essentially constant. At S-band wavelengths the slope appears to be a function of bird size.

The nature of the scattering mechanism that leads to a log-normal density function for radar cross sections of birds is not understood, and no attempt at analysis or explanation is made in this article. A brief description of the log-normal density function—of its properties and characteristics—is, however, in order.

The probability density function of a random variable x whose logarithm is normally distributed is

$$p(x,a,s) = \frac{1}{xs\sqrt{2\pi}} \exp \left\{ -\frac{1}{2s^2} \left[\ln \left(\frac{x}{a} \right) \right]^2 \right\}; \ (x > 0)$$
$$= 0; \ (x \leq 0)$$

where s is the standard deviation of the natural logarithm of x and a is the median value of x (s is used in place of the usual σ to avoid confusion with the radar cross section). It is convenient to characterize $p(x,a,s)$ by the parameter ρ, the ratio of the mean to the median values, as follows:

$$\bar{x} = \exp \left(\frac{s^2}{2} + a \right)$$

so that

$$\rho = \frac{\bar{x}}{a} = \exp \left(\frac{s^2}{2} \right)$$

Thus, the parameter ρ may be considered a measure of the fluctuations, directly related and proportional to the variance s^2. The greater the fluctuations in the variable—that is, the variance s^2—the greater the difference between the mean and the median and, in turn, the ratio ρ. Figure 5 shows the theoretical log-normal cumulative probability distributions in terms of ρ and the ratio x/a. Again, the distributions are straight lines whose slopes increase with increasing fluctuations—that is, with increasing ρ and s^2. At a ρ of 1.0, there are no fluctuations, s^2 is zero, and the distribution approaches a delta function.

The mean-to-median ratio, ρ, for each bird and radar band was calculated and is shown in Table 1. As noted earlier, the data of Figs. 2–4 and Table 1 suggest that the fluctuations in the radar signal, characterized by the slope of the curve (that is, ρ), are functions of the size or the distribution of physical area of the bird relative to the wavelength of the electromagnetic radiation.

The dimensional relationships for birds have been investigated by Greenwalt (*11*). For objects in a set of dimensionally similar objects, animate or inanimate, a volume or a mass will be proportional to the cube, and a surface to the square, of some linear dimension. A single dimension may be used to characterize a particular object in a set of dimensionally similar objects. Greenwalt (*11*) found that all birds are dimensionally similar, and that the scatter in his data is primarily due to the mode of flight—that is, flying versus soaring.

Let us consider overall body length (beak to tip of tail) to be the characterizing dimension for the birds. Unfortunately, the individual birds used in the experiments discussed here were not measured, so average values, taken from Greenwalt (*11*), for a bird species must be used. A plot of (i) the ratio of bird length to radar wavelength versus (ii) the mean-to-median ratio, ρ, from Table 1 is shown in Fig. 6.

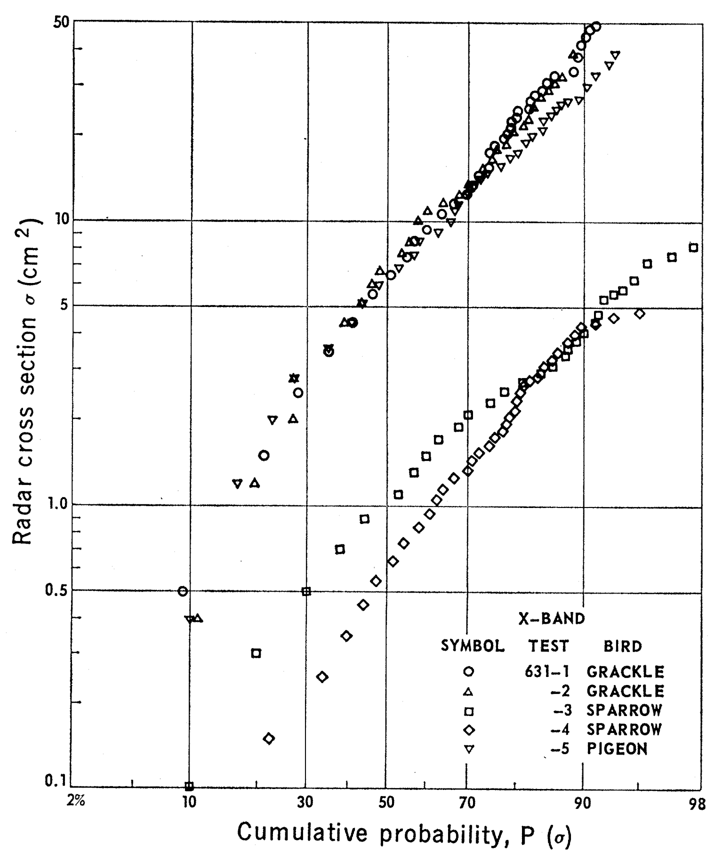
A general relationship between the physical size of the bird target relative to the radar wavelength and the measured fluctuations in the returned signal is indeed indicated. When the size-to-wavelength ratio is high, the ratio ρ is high, and vice versa. The data are not sufficient, however, to allow one to draw conclusions as to the detailed shape of the curve.

Using the general relationship given above, we may interpret the behavior of the probability distributions as a function of bird size and wavelength. At X-band wavelengths (Fig. 2), all the birds apparently are large relative to the wavelength and the radar is very sensitive to changes in aspect angle, wing motion, and so on. Hence, the large fluctuations—that is, large ρ.

At ultrahigh frequencies (Fig. 4), all the birds apparently are small relative to the wavelength, and the bird appears more like a point source. The fluctuation and ρ are small. The data for the duck (*8*) that are included in Fig. 4 show a ρ of 1.02. The size of the duck targets is given in terms of their weight, which ranged between 2½ and 4½ pounds (1 and 2 kilograms). The size-to-wavelength ratio for the ducks, in any case, will be less than 1.0. It should also be noted that the fluctuations are a result of head and neck motions only, since the duck was standing.

At S-band wavelengths (Fig. 3), we find a variation in the slope of the curves as a function of bird size. The lengths of the pigeon and the two grackles are large with respect to the wavelength, and the slope of the curve remains high, essentially the same as at X-band wavelengths (see Figs. 2 and 3 and Table 1). For both sparrows the values of ρ are low at S-band wavelengths, as at UHF wavelengths. This may indicate that the sparrows are small relative to the S-band wavelength.

The use of radar cross section alone as an indicator of bird size is not completely satisfactory because of the resonant effects discussed above. The data of Figs. 2, 3, and 4, however,



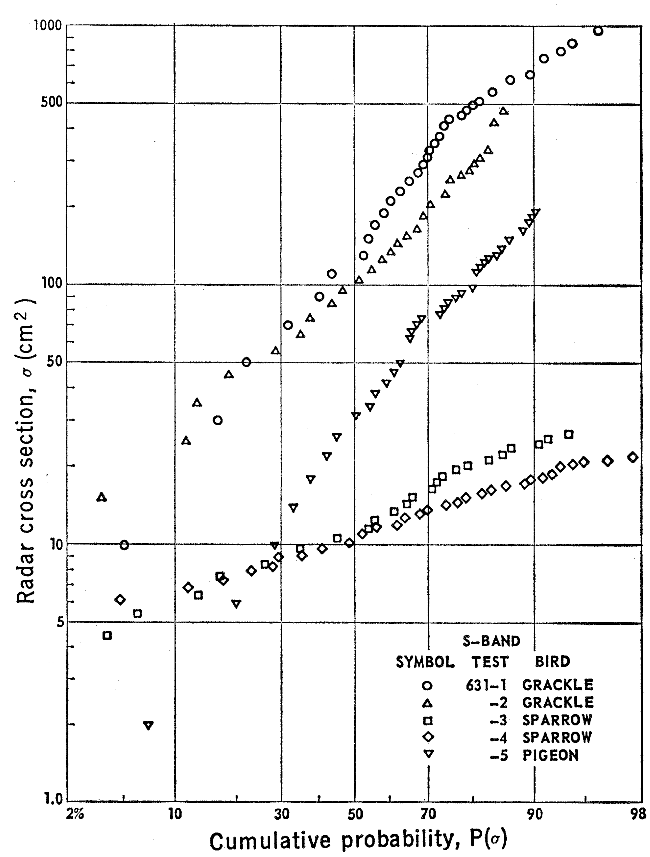


Fig. 2 (left). Probability distributions of the radar cross sections for all bird targets, at X-band wavelengths. Fig. 3 (right). Probability distributions of the radar cross sections for all bird targets at S-band wavelengths. For the sake of clarity, data for tests 631-1 and 631-2 are plotted too high by one order of magnitude.

indicate that the statistical properties of the cross section are independent of the magnitude of the radar cross section and are a function of the physical size of the bird relative to the radar wavelength. Figure 6, then, can be used to determine the size of the bird being observed. If only one radar wavelength is available, then one can determine only that the size of the bird is greater than or less than the wavelength. With several radars, however, one can determine a range of sizes within which the size of the unknown bird target must lie.

Fluctuations in the intensity of the signal received from a bird are due, as mentioned above, to the relative motions between the various parts of the bird and to changes in aspect. The way in which each part contributes to a power spectrum of the signal intensity depends upon the species, the radar wavelength, the mode of flight, and other factors, in an undetermined manner. However, a general intuitive model of a bird in flight may be used as a

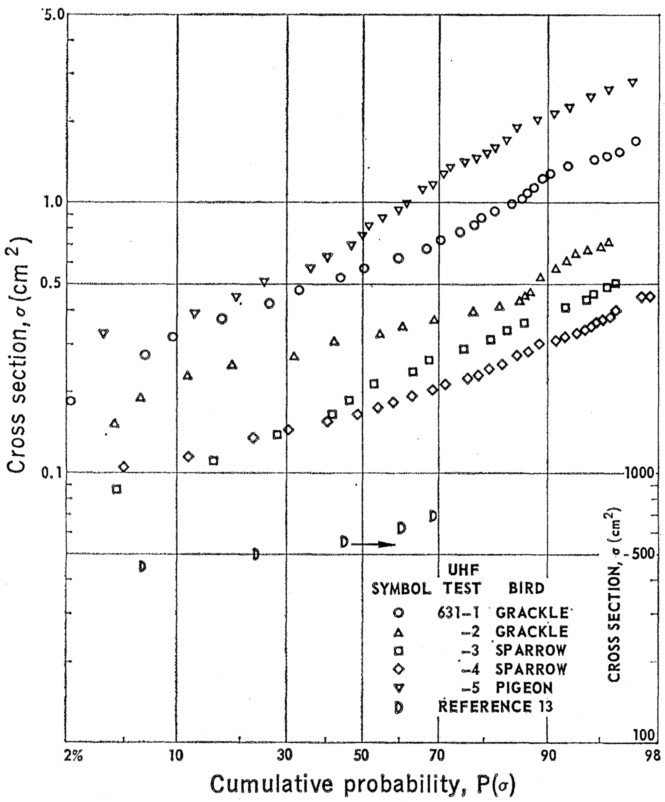
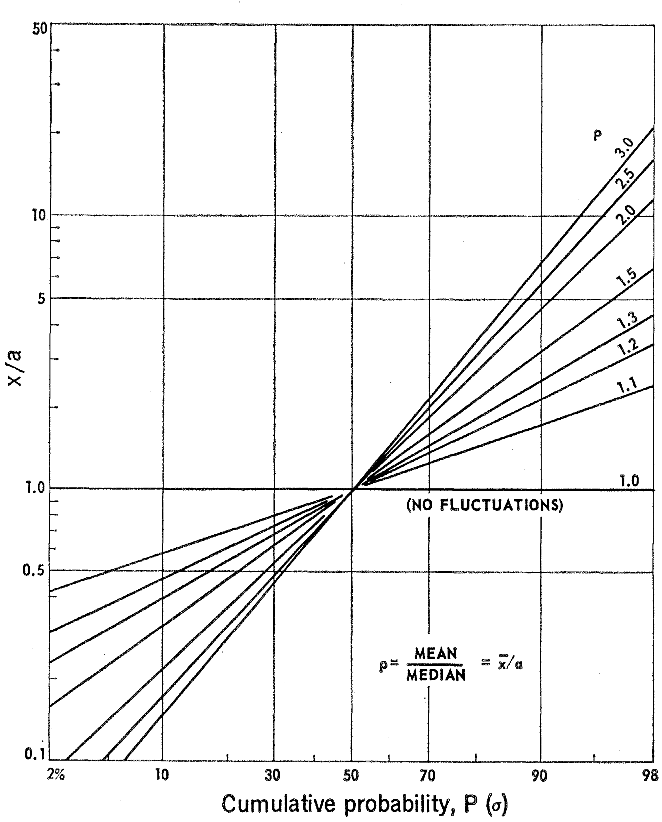
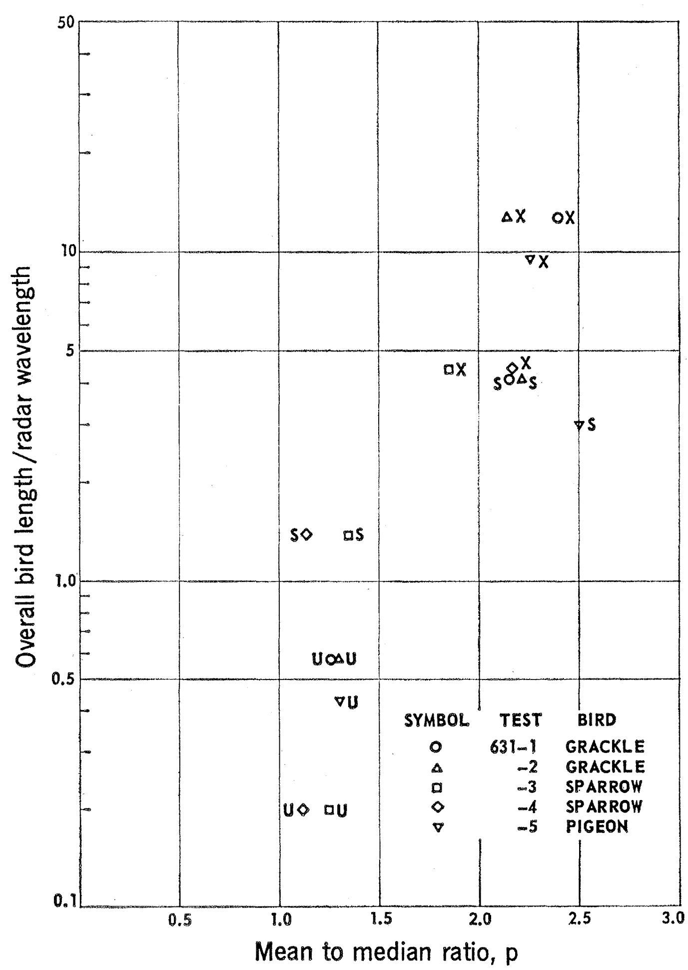


Fig. 4 (left). Probability distributions of the radar cross sections for all bird targets at UHF wavelengths. *D*, duck. For the sake of clarity, data for tests 631-3 and 631-4 are plotted too high by one order of magnitude and data for test 631-5 is plotted too low by one order of magnitude.

Fig. 5 (bottom left). Theoretical distributions for a random variable, *x*, whose logarithm is normally distributed.

Fig. 6 (bottom right). Effect of the physical bird size relative to the radar wavelength on the fluctuation in radar signal. Letter with symbol indicates radar band.





basis for qualitatively predicting, and for interpreting, the spectra resulting from such flight. In this model it is assumed that a bird is composed predominantly of a small number of individual scattering elements—body, head, wings, tail, and possibly smaller elements, such as feet and feather tips. If the motion between the scattering elements is assumed to be relative and the cross sections of the individual elements are assumed not to change with time, the results of considerable work on particle scattering may be used in establishing general features of the spectra. Atlas (*12*) and others show that, for such targets, the power spectrum of the signal intensity will contain a relatively large amount of power at frequencies, F, about zero and lesser amounts at frequencies corresponding to the differences in the radial velocities, Δv, between all pairs of scattering elements. They show this by using the Doppler equation

$$F = \frac{2\Delta v}{\lambda}$$

where λ is the radar wavelength. The power at each frequency F is proportional to the amplitudes of the individual signals from the two scattering elements whose relative radial motion yields the frequency F. If these relative radial motions are uniform, the spectrum will contain delta functions at each frequency F. If the motions are not uniform there may be some spread in the spectrum about each frequency F.

If the cross section of the scatterers is now assumed to change with time, then spectral components which are independent of Doppler velocities will result. If such changes in the cross sections are regular—as may be expected, since the wingbeat is approximately harmonic (*11*)—then corresponding spectral components may again be expected, due to modulation effects, at frequencies other than those near zero (*13*). Thus, on the basis of an intuitive model, salient spectral components at frequencies other than those near zero may be anticipated for birds, due to Doppler velocities or regular changes in cross section, or both.

Power spectra of the intensities of the received X-band, S-band, and UHF radar signals, recorded simultaneously at a rate of 20 points per second over a 15- to 30-second interval, were obtained for each bird species of Table 1. In each case, a relatively large peak in each spectrum around zero frequency was evident. Each of the X-band spectra also contained a second definite peak. The S-band spectra, except for the sparrow of test 631-3, showed such peaks also, but the peaks were less pronounced than those of the X-band. The UHF spectra generally exhibited a number of peaks at higher frequencies, less well defined than those of the S- and X-band. Thus, it appears that there is a clear trend toward a more definite high-frequency peak at the shorter wavelengths. Figures 7, 8, and 9 show X-band, S-band, and UHF spectra, respectively, for a grackle. The UHF

Table 2. Summary of bird cross-section data. [Data for starling, pigeon, sparrow, and rook, from Edwards and Houghton (*5, 6*); data for turkey buzzard, from LaGrone *et al.* (*7*); data for duck and chicken, from Blacksmith and Mack (*8*).]

Radar band	Aspect*	Radar cross section σ (cm²)
	Starling (Sturnus vulgaris)	
X	Head	1.8
X	Broadside	25.0
X	Tail	1.3
	Pigeon (Columba livia)	
X	Head	1.1
X	Broadside	100
X	Tail	1.0
	House sparrow (Passer domesticus)	
X	Head	0.25
X	Broadside	7.0
X	Tail	0.18
	Rook (Corvus frugilegus)	
X	Broadside	250
	Turkey buzzard	
X	Unknown	25 to 250
	Duck and chicken	
UHF†	Head	600
UHF†	Tail	24

* For the cross-section measurements of the starling, pigeon, sparrow, and rook, the birds were suspended from a tower with their wings folded; the radar elevation angle was 18 degrees. Measurements of the turkey buzzard were made when the bird was in flight; measurements of the duck and chicken were made when the birds were standing or squatting. † 400 megacycles.

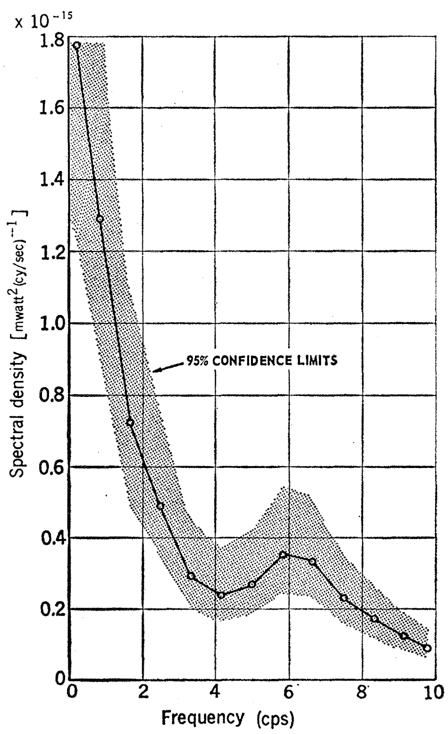


Fig. 7. Spectrum of fluctuations in the received radar signal from a grackle (test 631-1) at X-band wavelengths.

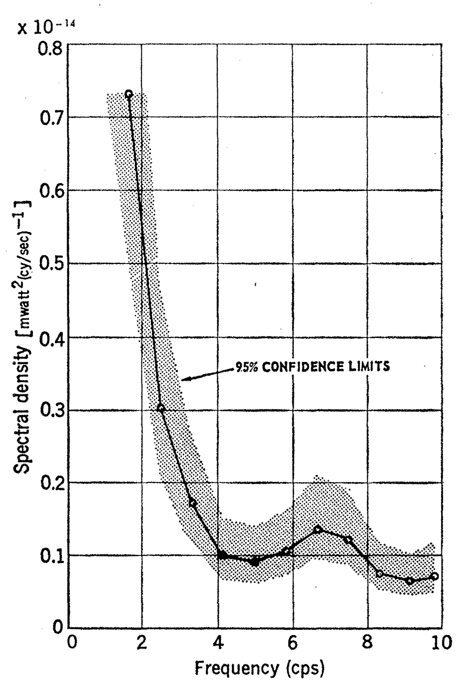


Fig. 8. Spectrum of fluctuations in the received radar signal from a grackle (test 631-1) at S-band wavelengths.

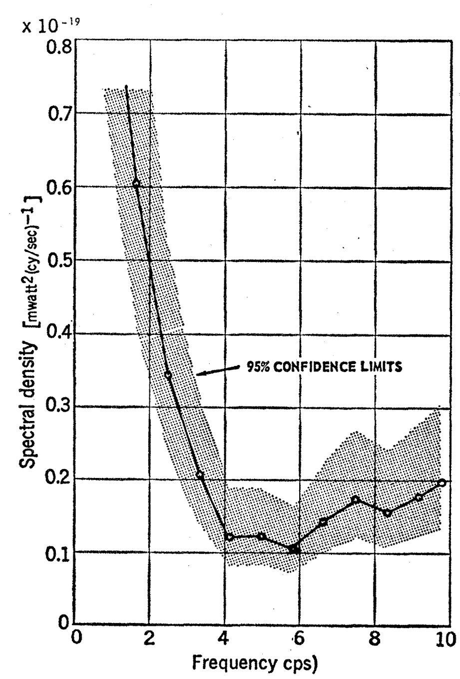


Fig. 9. Spectrum of fluctuations in the received radar signal from a grackle (test 631-1) at UHF wavelengths.

spectrum of Fig. 9 indicates folding about the Nyquist frequency of 10 cycles per second. This folding, which was also apparent in other spectra, prevents determination of the true location of the higher-frequency peaks. However, even if the true frequency at the peak had been determined, there is no sound theoretical basis for relating the peak frequency to any visually observed bird motions, such as wingbeat. The relationship between bird motions and spectral peaks, the spread in the spectrum about the peaks, and the ratio of the areas under the spectral peaks to the total spectral area may be cataloged for different species through experimentation. Such a catalog would be useful in the identification of bird species by radar, but its compilation is beyond the aim of the investigation discussed here.

It seems clear, however, that the presence of distinct spectral components at frequencies other than zero, as recorded in these investigations, must be associated with relative motions between the moving parts of a bird. Certain single insects may yield fluctuation spectra similar to those of birds, but insects can be distinguished from birds by their cross sections (*14*). It is highly unlikely that meteorological targets can yield fluctuation spectra having distinct peaks at frequencies other than about zero; thus, a real-time spectal analysis of dot angles should permit their immediate classification as either meteorological, bird, or insect echoes.

Conclusions

A bird in flight is a complex target and produces a highly fluctuating radar return. Thus, the radar cross section should be described in terms of its statistical properties. The radar cross sections have no simple wavelength dependence. The radar return does, however, contain information which provides a basis for identifying an unknown point target as a bird. This information is the radar cross section, the probability distribution of the cross section, and the fluctuation or energy spectrum. The radar cross section of (or power received from) a single bird in flight has a log-normal distribution. The characterizing parameter is the mean-to-median ratio of cross section, which represents a measure of the amount of fluctuation in the returned signal. This ratio, in turn, is a function of the size of the bird relative to the radar wavelength. The fluctuation spectrum contains peaks at frequencies other than zero, which indicate periodic, relative motion within the target—for example, the bird's wingbeat.

Thus, the radar return from single birds in flight differs characteristically from the returns from other possible point or dot targets, such as aircraft, swarms of insects, several birds together, or small clouds or other meteorological structures.

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Free Enterprise in Data Compilation

Committees are urged to open a freeway for compilers rather than to guide and channel their steps.

K. Way

This article is concerned with ways to increase the number and quality of compilations of scientific data. Three papers have recently appeared in *Science* on programs to achieve this end (*1–3*). I propose here to examine a fundamental assumption of these three approaches, to argue against it, and to suggest an outlook to replace it. The assumption is that in the future compiling will not be performed adequately without special inducement, planning, and guidance by distinguished committees or panels.

In his paper on "International cooperation: the new ICSU program on critical data," Brown (*1*) tells of plans for an international committee, CODATA, to conduct a worldwide survey of existing compilation activities on the basis of which ". . . CODATA will attempt to *assess* the needs of science and industry for additional compilations of evaluated data" (page 753, italics mine).

Brady and Wallenstein, in their article on "The National Standard Reference Data System" (*2*), envisage (page 756) "the *planning* and implementation of projects for compiling data." Later they note (page 761) the desirability of "a directive to the Secretary of Commerce to provide or *arrange* for the collection, compilation, critical evaluation, publication, and dissemination of standard reference data . . ." (italics mine).

Overhage, in "Science libraries: prospects and problems" (*3*), sees planning (plus incentive) as the answer. "As al-