Richardson, W.J. 1979. Radar techniques for wildlife studies. p. 171-179 *In*: PECORA IV/Proceedings of the Symposium/Application of remote sensing data to wildlife management. Sci. Tech. Ser. 3. Nat. Wildl. Federation.

Radar Techniques for Wildlife Studies[1]

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Abstract.--This paper reviews (1) the capabilities and limitations of various types of radars for detecting and studying airborne animals (birds, bats, insects), (2) factors affecting detection range, (3) the 'state of the art' of target identification, and (4) promising radar techniques for future wildlife studies.

§1. INTRODUCTION

Radars transmit radio energy into the airspace, detect any echoes that are returned, and display information about those echoes. The radio emissions are usually short, widely-spaced pulses, so distance to an echo-producing target can be determined from the time taken for the echo to return. Emissions are beamed in a particular direction, so the direction of the target is also known.

Radars are usually designed to detect aircraft, missiles, mortar shells, ships, buoys, terrain, or severe weather. However, airborne birds, bats and even insects are sometimes detectable. Measurable parameters can include (depending on radar and target type) numbers aloft, concentration areas, altitudes, flight directions and speeds, approximate target sizes, and wingbeat frequencies. With moderate- or high-power radars, at least some of these parameters are measurable at least several km away, in daylight or darkness, and sometimes above or even in clouds. Data can often be recorded photographically, thus facilitating continuous monitoring. For these reasons, radars have become the principal tools in studies of 'bird migration in progress'. Applications include estimating numbers migrating over an area (e.g., Alerstam 1977) and studies of migration timing re weather (Richardson 1978), routes (e.g., Bellrose 1964), orientation (e.g., Emlen & Demong 1978), flight physiology (e.g., Emlen 1974; Schnell 1974) and local 'roosting' movements (e.g., Eastwood *et al.* 1962; Williams *et al.* 1973). Radars are also widely used in bird hazard to aircraft studies (Blokpoel 1976).

Unfortunately, radars also have severe limitations in wildlife studies. Targets are usually difficult to identify, and adjacent targets (e.g., individual birds within flocks) are not resolved. Results are often not quantitative, detection probability often depends on altitude, and fast-moving flocks are often overrepresented (Richardson 1972a, 1978). Care must be taken to recognize the various limitations, and to avoid or compensate for them whenever possible.

Operational radars first appeared during World War II, and birds and insects sometimes were detected even by these comparatively low-powered instruments. However, biologists did not use radars to any significant extent until the late 1950's (for birds), mid-1960's (insects) or late 1960's (bats). While radars can detect certain objects on the ground (see §5), to date biologists have used radars only to detect airborne animals--primarily birds. Myres (1970) gives a comprehensive (to 1969) list of papers reporting detection of birds, bats and insects, and Eastwood (1967) gives a detailed summary of 'radar ornithology' up to the mid-1960's. Schaefer (1976) and Ireland *et al.* (1976) are recent detailed accounts of insect and bat detection by radar.

§2. TYPES OF RADARS

Almost any type of radar can be useful in certain wildlife studies but capabilities vary widely. Powerful radars give a broad but often only qualitative view; smaller radars reveal more detail about individuals, but only in a local area. Tracking radars provide more detail than surveillance radars, but require continuous attention and more data processing. Some problems can only be addressed by using two disparate radars simultaneously. General accounts of radar technology include Barton (1964), Nathanson (1969) and Skolnik (1970). Information about most specific radar

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[1]Paper presented at Pecora IV: Application of Remote Sensing Data to Wildlife Management, Sioux Falls, S.D., Oct. 10-12, 1978. Published by National Wildlife Federation, Washington, D.C.

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models can be found in one or more of Anon. (1965), Battan (1973:276*ff*), Barton (1975), *Jane's Weapon Systems*, various issues of *Aviation Week & Space Technology*, and the catalogue of Radio-Research Instrument Co. (3 Quincy St., Norwalk, Conn.). All types of radars in Table 1 have been used in ornithological studies, and some in bat and insect studies.

The well-known 'Plan Position Indicator' or PPI display (Fig. 1) is used with radars whose beams rotate horizontally (Table 1A,B). Number, extent and positions of echoes are directly evident on the PPI, and flight directions and speeds become evident over time as the echoes move. Time exposures (Fig. 2) and time-lapse techniques (Phelp & Downie 1962; Solman 1969; Williams & Mix 1973; Yacobi & Baturov 1974) are used to record data for subsequent analysis. The chief limitations of

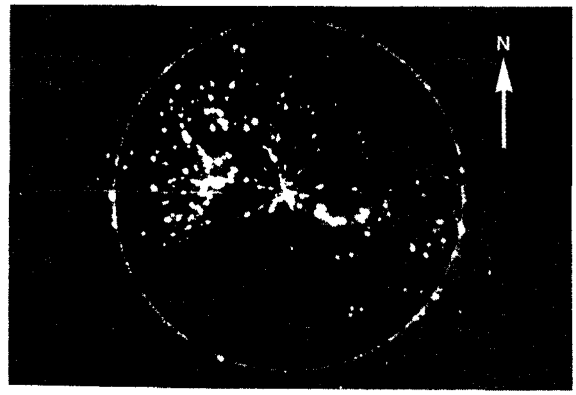


Figure 1.--Southeastward bird migration visible on PPI of ASR-5 airport surveillance radar near Halifax, N.S. Each echo is a bird or flock. Circle denotes radius of 5 n.mi.(9¼ km).

Table 1.--Characteristics and applications (emphasizing bird studies) of various radar types. ++ = very suitable, + = suitable, ± = some capability (often difficult), − = unsuitable.

Radar type	Typical characteristics						Parameters measurable[5]									
					Beam width[4]											
	Band[1]	kW Peak Power	Range[2]	Pulse Duration[3]	Horizont.	Vertical	Chronology	Routes	# Flocks	# Birds	Bearing	Distance	Height	Course/Speed	Grouping	Signature
A. FAN-BEAM SEARCH																
Ship navigation	X-S	25	S	SM	2°	20°	+	±	+	+	++	++	−	++	±	−
Airport surveil.	S	400	SM	M	1½	20	++	±	++	±	++	++	−	++	−	−
Air route; military	S,L	5,000	ML	ML	1	10	++	++	++	−	++	+	−[6]	+	−	−
B. PENCIL-BEAM SEARCH																
Weather surveil.	C,S	500	ML	ML	2	2	++	++	±	+	++	++	±	++	−	−
Mod. Ship/Airborne[7]	X	25	S	SM	2	2	+	±	−	+	++	++	+	+	±	±
Tracking (search mode)[8]	X-	40-	SM	SM	1-2	1-2	±	±	±	±	++	++	+	+	±	−
	S	5,000	ML	M	½-1	½-1	±	+	±	±	++	++	+	+	−	−
C. HEIGHT FINDERS																
Precision approach	X,C	150	S	SM	5	1	±	−	±	±	±	++	++	−	±	−
Surveillance	C,S	4,000	ML	M	3	1	±	±	±	−	±	+	+	−	−	±
D. VERTICAL BEAM	X	25	S[9]	SM	2	2	+	−	−	+	−	−	++	−	±	±
E. TRACKING[8]	X-	40-	SM	SM	1-2	1-2	−	−	−	−	++	++	++	++	+	++
	S	5,000	ML	M	½-1	½-1	−	±	−	−	++	++	++	++	+	++

[1]See §3 for band (wavelength) designations.
[2]Usable range for biological targets; S=short (<5 km), M=Medium (5-30 km), L=Long (>30 km).
[3]Short (<½ μsec), Medium (½-2 μsec) or Long (>2 μsec); corresponding range resolutions are <75 m, 75-300 m and >300 m.
[4]Corresponding resolutions (in km) ≈ Range (km) x sine (Beamwidth).
[5]Parameters 1-4 concern multiple targets; 5-10 concern individual targets.
[6]Roughly measurable on multiple-beam (3 dimensional) radars.
[7]Ship navigation or aircraft weather radar with dish antenna (see Graber & Hassler 1962; Schaefer 1976).
[8]Upper and lower lines give characteristics of low and high power trackers, respectively.
[9]Range is measured vertically in this case.

Figure 2.--Time exposure (1.75 min) of PPI of Halifax ASR-5 radar. Each streak is the path of a bird or flock going ∿SE.

fan-beam search radars are (1) lack of height data, (2) poor resolution and inability to detect low-flying targets at long range, (3) suppression of some weak echoes by special circuitry--see §3, and (4) lack of detail about single targets. Pencil-beam search radars provide height data, but do not scan the entire airspace. Weather radars are especially useful because they are calibrated to permit measurement of echo intensity (Gauthreaux 1970, 1974).

The 'Range Height Indicator' or RHI display (Fig. 3) can be used with pencil-beam and specialized height-finding radars when the beam nods up and down. Height-finding is the main application, but some other parameters can be measured (Table 1B,C). When targets are numerous, resolution on long-range height finders is often inadequate for quantitative studies (Fig. 3). Precision approach radars have much better resolution and accuracy, but may not detect high-altitude biological targets (e.g., Sutter 1957; Hunt & Blokpoel 1973).

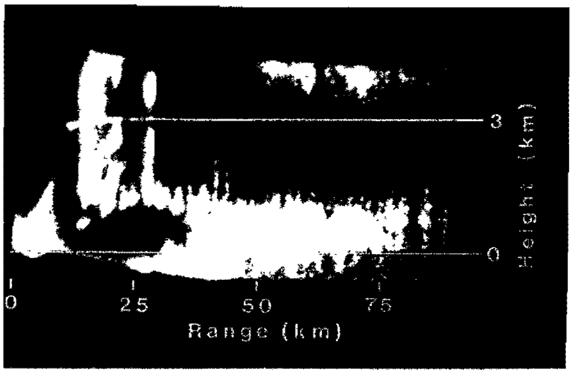


Figure 3.--Range Height Indicator showing dense layer of unresolvable bird echoes at low altitude and cloud ∿4 km aloft. Within 30 km birds are hidden by terrain echoes.

A 'Time vs Height' record can be obtained from a radar having a fixed vertically-pointed beam. From this, numbers aloft at various heights and times can be determined (Table 1D).

Tracking radars have been used, since the late 1960's, to obtain more detailed information about single bird, bat or insect targets (often single individuals). The beam of a tracking radar, once pointed at an object, automatically follows it across the sky. Echo strength and position (in 3 dimensions) are recorded with every pulse--several hundred times/sec. Wingbeat frequency and 'flap-glide' pattern can often be determined from the 'amplitude signature' (Fig. 4). Some tracking radars can also record the Doppler shift of the echo. Tracking radars can also be used in a search, height-finding or vertical beam mode. For techniques, see Bruderer & Steidinger (1972), Williams & Williams (1972); for examples of precision applications, see Larkin *et al.* (1975), Able (1977), Emlen & Demong (1978). A brief discussion of Doppler radars is included as an Appendix.

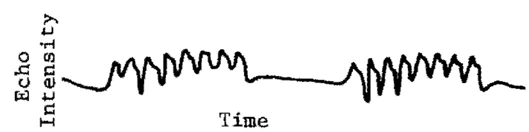


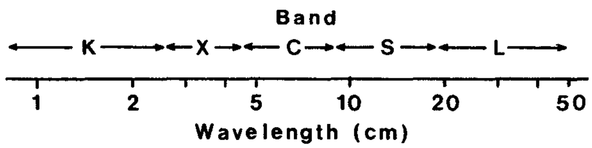
FIGURE 4.--Amplitude signature of a White-throated Sparrow tracked by FPS-16 C-band monopulse tracking radar (from Williams & Williams 1972). Two 'flapping' periods (each with 8 wingbeats) separated by 'glide' periods are shown. Record length is 1½ sec.

§3. RANGE CAPABILITY

Radars can detect small animals at surprisingly long distances. One reason is that an inverse square spreading rule applies to both outgoing and returning energy. Hence, a target with 0.0001 times the cross-sectional area of another (e.g., bird vs aircraft) can be detected 0.1 times as far away. Also, water (the main component of animal tissue) reflects a high proportion of the incident radar energy--about 60% as much as would a comparably-sized metal object. Furthermore, the average echo intensity from a group of targets too close to be resolved is the sum of their individual echo intensities. Thus, a flock of waterfowl can produce 'point' echo comparable to that from a small aeroplane. Maximum detection ranges of the 3 radar types listed in Table 1A would be about ½, 5 and 35 km for a single Starling, and 5, 50 and 150 km for a large flock of geese.

On a long-range low resolution radar (3 μs pulses; 1° horizontal beam width), targets at all heights above a 450 x 700 m area would be unresolved at a range of 40 km. Every such volume of airspace will contain at least 10 small birds when even a modest broad-front nocturnal migration is in progress, and 50+ birds during a dense broad-front migration. Echoes from such migrations often saturate radar displays at ranges of 0-45 km.

Most radars produce energy with a specific wavelength within the range 1-50 cm. This range is traditionally divided into several bands:



The intensity of echo from large targets is proportional to target cross section. However, when target dimensions(d) are small re wavelength (λ), echo intensity $\propto d^6/\lambda^4$. Thus, rain drops produce far more echo than the smaller droplets in clouds. Clouds and rain both produce far more echo at K or X band than at S or L band. Radars designed to detect weather systems operate at short or moderate wavelengths; those to detect aircraft often operate at longer wavelengths to minimize weather echo. Similarly, insects produce strong echoes only at short wavelengths, whereas birds (and presumably bats) produce strong returns at all but the longest radar wavelengths (Glover *et al.* 1966; Konrad *et al.* 1968). In practice, insect echoes can be a significant source of confusion in ornithological studies with X-band radars (e.g., Bruderer 1971; Blokpoel & Burton 1975), but are rarely detectable at normal working ranges on S- and especially L-band radars.

Average echo strength from an aircraft, bird or insect (and presumably bat) is larger when the broadside rather than the head or tail aspect faces the radar (Edwards & Houghton 1959; Bruderer & Joss 1969; Houghton 1969; Nathanson 1969; Schaefer 1976). Thus, targets are often detected at greater range if moving tangentially than if moving radially, and unidirectional, broad-front bird or insect flights often saturate a roughly elliptical rather than circular area of the PPI (e.g., Richardson 1976:Plate 5; Schaefer 1976:162*ff*). However, many radars, especially those designed for aircraft detection, have Moving Target Indicator (MTI) circuits, which suppress echoes from targets that have little or no radial velocity. MTI is useful for detecting birds in the presence of echo from terrain, but with MTI only the birds moving at least partly towards or away from the radar are detectable (Fig. 2). Even they are partly suppressed, especially if a headwind reduces their ground speed. MTI and other radar circuits are often necessary, but can seriously reduce detection range and the usefulness of radars as quantitative instruments (Richardson 1972a).

§4. IDENTIFICATION

Uncertainty about target identity is one of the main limitations of radar. Visual identification is only occasionally possible, since one of the main uses of radar is to detect targets that cannot be seen. Echo characteristics and behaviour usually form the only available basis for partial or complete identification.

Useful visual information can, on occasion, be obtained in at least four ways: (1) An observer in an aircraft or ground vehicle can be directed by radio to the location of a radar target (Hofmann 1956). However, this method is expensive and difficult, especially at night (but see Weitnauer 1956) or if the radar has no height-finding ability. (2) A telescope mounted on the antenna of a tracking radar can be used to identify nearby targets in daylight (e.g., Harper 1958; Gehring 1967; Houghton 1969; Ireland & Williams 1974). (3) A sighting of a bird or flock can occasionally be associated at a later time with a specific echo visible on a radar photograph, but only if few targets are present or if the target is very intense or distinctive, such as a dispersal from a bird or bat roost, or a waterfowl flock (Sutter 1957; Eastwood *et al.* 1962; Gehring 1963; Grimes 1973; Williams *et al.* 1973; Blokpoel 1974). (4) If general visual observations show that one species predominates, that species is probably the one responsible for corresponding activity detectable simultaneously by radar; however, the radar might also be detecting high-altitude, invisible targets.

Echo characteristics and behaviour provide many clues about target identity. Inanimate targets are usually easily recognized, especially on time-lapse PPI films:

- terrain produces intense, extensive, stationary echoes
- vehicles produce point echoes that move along consistent routes
- waves give non-persistent, scintillating echoes
- ships give intense, slow-moving echoes
- aircraft echoes move rapidly; often disappear at known airports
- precipitation and cloud echoes are usually

extensive; often characteristic in shape; move slowly in a uniform direction

In contrast, birds, bats and insects produce point echoes, often weak, that move slowly in variable directions; when many are aloft, the point echoes merge into an extensive mass of echo at close range, but are resolved around the edges of the mass.

Bat echoes have been little studied, but seem generally similar to bird echoes. Bats fly almost exclusively at night, often too low to be detected by radar. When they leave large roosts, 'blossoming' echoes can appear on the PPI; such echoes recur nightly, can often be identified visually, and can provide useful data about bat activity (Grimes 1973; Williams *et al.* 1973; Ireland *et al.* 1976). In much of North America, observations of silhouettes against the moon show bats to be much less numerous than nocturnal bird migrants, and thus an insignificant source of contamination during ornithological studies. With tracking radars, bats may be recognizable by their erratic paths and amplitude signatures (Bruderer 1969), but more study is needed.

Insects are detected primarily by short-wavelength radars (§3). In comparison with birds, echo intensities and airspeeds tend to be lower, and wingbeat rates (sometimes evident from amplitude signature if a tracking radar is used) tend to be higher. However, large insects and small birds can be difficult to distinguish, especially when only echo intensity (not track, speed or signature) is recordable (e.g., Blokpoel and Burton 1975). Schaefer (1976) discusses use of signatures to distinguish major groups of insects.

Birds can often be identified to major group from the behaviour of their echoes. Daily local movements of blackbirds, Starlings, gulls or waterfowl to and from roosts are very characteristic and amenable to visual verification. Migration departures from such roosts are also occasionally evident (e.g., Harper 1959; Richardson & Haight 1970). Migrating hawks are often recognizable by their tendency to fly at mid-day and to form lines of echoes (Gehring 1963; Houghton 1970; Richardson 1975). Sometimes a species or group is known to migrate in an unusual direction at a specific season, and corresponding echoes appear on radar (e.g., Richardson in press). Nocturnal, broad-front migrations of passerines are recognizable by the rapid appearance of immense numbers of weak, slow-moving echoes about ½ hr after sunset.

The detailed characteristics of individual echoes recordable on tracking radars provide further clues to identity. Airspeed, echo intensity, wingbeat rate, and the temporal pattern of flapping and gliding are all potentially useful. However, for most of these variables there is both overlap among species and intra-specific variation (Bruderer *et al.* 1972; Emlen 1974; Vaughn 1974; Pennycuick 1975). Seemingly appropriate multivariate classification methods have not yet been applied to the identification problem. Another complication is that echo intensities and signatures become much more difficult or impossible to interpret when the target consists of more than one bird (Houghton 1969; Houghton & Blackwell 1972; Flock 1974).

In summary, reliable identification to species level is now rarely possible from echo behaviour or characteristics alone. Improvements are possible by making more use of the data contained in echo signatures, but physical differences among many species are so slight that their echoes will remain indistinguishable in the foreseeable future. Fortunately, species-level identification is not essential in some types of studies, since related species often behave similarly.

§5. FUTURE OPPORTUNITIES

Foreseeable opportunities for expanded use of radars in wildlife studies are of two kinds: (1) use of standard methods and presently available radar equipment in circumstances where they are not now used, and (2) development of new methods and applications.

Several hundred medium- and high-power search radars (air traffic control, military, weather) suitable for ornithological studies are presently operating in North America. Locations of most can be found by reference to the FAA Air Traffic Service Fact Book, Macdonald (1971:22), Scholin (1977) and aeronautical maps, or by contacting the operating agencies (FAA, NOAA and USAF in the U.S.A.; MoT, AES and CAF in Canada). It is often possible to obtain biological data from such radars while they are being used for their normal purpose, or when they are not being used. Local and migratory movements of birds have been studied at only a small minority of these sites. These radars are suitable for studies of the patterns, routes and timing of bird movements. Such radars have also been used to study bat movements, but in most areas it is doubtful whether bats are sufficiently common or concentrated for search radar to be a useful technique.

Because bird migration is inherently a large-scale phenomenon, some aspects can only be understood if simultaneous observations are made over an area even larger than that covered by a long-range radar (Lowery & Newman 1966). Simultaneous studies at several radar sites are possible (Bellrose 1964; Richardson & Gunn 1971) but logistically difficult. Flock & Bellrose (1970) showed that several widely-separated radars could be monitored successfully at an FAA Air Route Traffic Control Centre, and Beason (1978) used this capability to monitor six radars simultaneously over 4 migration seasons. However, radar data are now digitized before transmission to civil and military control centres. Although some bird echoes are digitized and transmitted (Richardson 1971, 1972b), a variable but often large fraction are suppressed by special radar circuitry or the digitizer. Thus, radar data from remote sites are now highly biased and unsuitable for quantitative studies (Richardson 1972a), and a valuable source of broad-scale data no longer exists.

The continuing development of procedures that suppress non-aircraft echoes from aircraft surveillance radars (Klass 1973; Brown & Nucci 1975; East 1975; Hartley-Smith 1975; Taylor & Brunins 1975) makes it increasingly difficult to obtain unprocessed and relatively unbiased radar signals even at the individual radar sites. However, advances in search radar design are not all detrimental for purposes of studying wildlife. Pulse compression techniques can be applied to improve range resolution without decreasing maximum range. Doppler discrimination techniques can be used to enhance detection of small moving objects. Moving target detectors can now be built to consider azimuthal as well as radial motion (Anon. 1975). These features are not available on most existing radars, but can be expected to become more widely used.

Small search radars generally have the advantages of high resolution, portability, absence of circuits that suppress biological targets, and sufficiently modest cost and maintenance requirements to permit full-time use in biological studies. Such radars have been used infrequently to date (Graber 1968; Schaefer 1976; Williams *et al.* 1976), but would be valuable for many applications in which high resolution and quantification are critical. Their portability can partially compensate for their short range.

Use of radars in studies of terrestrial (as opposed to airborne) animals has rarely been mentioned. Gulls and other moderate or large sized birds resting on runways and other smooth surfaces can be detected by airport surface detection (ASDE) radars (W.F. Inglefield, in Busnel & Giban 1965:135; Schaefer 1969; Gauthreaux 1976). ASDE radars are used at some major airports to assist in controlling ground traffic, and might be useful in revealing bird hazards to aircraft, especially in poor visibility conditions. Personnel-detection radars might be useful for detecting large mammals, especially at night, but such radars are not yet generally available and it is not clear what advantages they would have over other sensors. Side-looking airborne radars (SLAR) are potentially valuable for studies of animal habitat, especially when resolution is enhanced by synthetic aperture techniques (de Loor 1976), but to my knowledge SLAR has not proven useful for direct detection of animals.

To date few biologists have used tracking radars despite their unparalleled capabilities in studies of the flight behaviour and orientation of airborne animals. In the cases of insects and bats, the only tracking radar work has been methodological rather than biological. Accessibility is a major limitation, since most tracking radars are operated by the military at locations where missiles are launched. However, a few civil tracking radars are operated by NASA and for weather research. Military surplus trackers have been used to advantage (e.g., Schaefer 1968; Griffin 1973; Larkin *et al.* 1975; Able 1977), but these often suffer from maintenance difficulties and have minimal provisions for recording data. Also, modern monopulse trackers provide more precise positional and signature data than older 'conical scan' trackers (Barton 1964; Skolnik 1970).

Beams of recent 'phased array' radars are steered electronically rather than by physical movement of the antenna (Kahrilas 1976). This allows great flexibility in scanning pattern, and allows instantaneous repositioning of the beam. On some radars the latter feature, in conjunction with computer control, permits interleaved tracking of two or more targets. This capability could facilitate studies of the spacing of airborne animals (*cf.* Eastwood & Rider 1966; Bruderer 1971; Balcomb 1977) and their reactions to aircraft (*cf.* Larkin *et al.* 1975). Phased-array radars have apparently not yet been used in biological studies.

In both biological and non-biological applications of radar, a main challenge is to find ways of recording and interpreting the large amount of potentially useful information contained in the echoes. Important advances are possible here. In search radar studies, numbers aloft are usually recorded by subjective examination of the PPI display or, less often, by laborious manual counting of echoes. Electronic counting methods have been developed (Clausen 1973; Hunt 1975-77) but in North America have been little used. Also, calibrated attenuation methods can be used to record the echo amplitude information that is normally suppressed by the PPI (Gauthreaux 1970, 1974; Hunt 1973). Extraction of information about flight directions from PPI photographs could be greatly facilitated by electronic aids (e.g., X-Y digitizers) that are now readily available.

Some radars have provisions to digitize echo position and amplitude for on-line or off-line computer processing. Such capabilities have rarely been used in biological studies, although several workers have made analogue tape recordings of radar signatures for subsequent digitization and computer analysis. Recent advances in electronics permit direct transfer of selected data from the receiver of any type of radar to a computer, at modest cost, even on radars not originally designed for such data acquisition (Larkin & Eisenberg 1978). Linkage of radars with computers can provide several advantages in wildlife studies: (1) More data can be made available with less need for time-consuming manual steps like photo interpretation. (2) Less distortion of data (e.g., echo amplitude) occurs, since analogue circuits and recorders with limited dynamic range or frequency response can be avoided. (3) Analysis of amplitude and Doppler signatures as clues to identity or flight behaviour is facilitated, since computation-intensive autocorrelation and spectrum analysis techniques are valuable in interpreting radar signatures. (4) Computer control of radar scanning or tracking pattern becomes a possibility on radars dedicated to wildlife studies. When item (4) becomes a reality, complex observation programs (e.g., Bruderer 1971) should be possible even when the radar is unattended.

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APPENDIX--DOPPLER RADARS

Radars able to detect the Doppler shift of echoes provide a direct measure of radial speed and enhanced ability to detect weak moving echoes in the presence of stronger terrain echoes. Small continuous-wave (CW) Doppler radars have been used to record flight speeds, wingbeat rates and Doppler signatures of birds (Schnell 1965; Flock & Green 1974). However, the simpler CW radars are limited in application by inability to measure range. Pulsed-Doppler radars can reveal range as well as bearing, speed and both Doppler and amplitude signatures (Green & Balsley 1974). They are potentially valuable in wildlife studies because they can measure so many echo characteristics.