ASSOCIATE COMMITTEE

ON

BIRD HAZARDS TO AIRCRAFT

NATIONAL RESEARCH COUNCIL, OTTAWA, CANADA

FIELD NOTE NUMBER

60

TEMPORAL VARIATIONS IN THE ABILITY OF INDIVIDUAL RADARS IN DETECTING BIRDS

W. JOHN RICHARDSON

OTTAWA

JANUARY, 1972

TEMPORAL VARIATIONS IN THE ABILITY OF INDIVIDUAL RADARS IN DETECTING BIRDS

W. John Richardson

Section of Neurobiology and Behavior

Division of Biological Sciences

Cornell University

Ithaca, N.Y. 14850

TABLE OF CONTENTS

INTRODUCTION
METHODS
-Tests on ASR-5 Radar
-Tests on AASR-1 Radar
-Tests on ASR-7 Radar
-Incidental observations of various radars
RESULTS AND DISCUSSION
-Power output
-Beam properties
  -Polarization
    -Linear vs Circular
    -Horizontal vs Vertical
  -Vertical Performance Diagram
    -High-flying birds nearby
    -Low-flying birds far away
    -Shadowing by hills
    -Stacked-beam radars
  -Anomalous propagation
  -Pulse volume
    -Effective beamwidth
    -Pulse duration
-Receiver properties
  -Type of Receiver
  -Tuning
  -Noise Figure
  -IF Gain
  -Sensitivity Time Control
  -Fast Time Constant and Pulse Length Discriminator
  -Instantaneous Automatic Gain Control and CFAR
  -Video integration
  -Coherent Moving Target Indicator
    -Description
    -MTI wedges
    -Suppression outside the wedges
    -Adjustable blind speeds
    -Range gating
    -Dynamic range limitations
  -Noncoherent Moving Target Indicator
-Channel changes
-Display adjustments
-Digitized radar data
IMPLICATIONS AND CONCLUSIONS
ACKNOWLEDGMENTS
LITERATURE CITED
FIGURES AND TABLES

INTRODUCTION

Ornithologists, radar engineers, radar meteorologists, the military, and to a lesser extent Air Traffic Controllers are now aware that most types of radars regularly detect birds (see bibliography in Myres, 1970; also Anon., 1969:8; Bruderer, 1969, 1971; Bruderer and Joss, 1969; Nathanson, 1969:168; Able, 1970a,b; Ferry, 1970; Gauthreaux, 1970, 1971; Gauthreaux and Able, 1970; Warden and Wyndham, 1970; Weishaupt, 1970; Blokpoel, 1971; Myres and Cannings, 1971; Richardson, 1971, 1972; Richardson and Gunn, 1971; Spiers et al., 1971).

It is also well known that different radars often have very different capabilities in detecting birds (eg., Bellrose, 1964; Myres, 1964a; Eastwood, 1967; Konrad et al., 1967; Flock, 1968; Schaefer, 1968; Blokpoel, 1971).

Day to day variations in the ability of a single radar in detecting birds seem to be less widely recognized. Eastwood (1967) has stated that such variations might result from differing properties of the bird targets (size, aspect, grouping, altitude) and from temporal changes in the characteristics of the radar equipment. While Eastwood (1967:82) indicates that modern radar equipment should not suffer from significant fluctuations in sensitivity, Nisbet (1963) and Gehring (1963) have reported such fluctuations.

Under the sponsorship of the Associate Committee on Bird Hazards to Aircraft of the National Research Council of Canada, surveillance radars at over 30 different Air Traffic Control and military sites in Canada have been used to study migration. During this work we have found that radars being used for aircraft detection are frequently adjusted. These adjustments sometimes produce pronounced changes in the number of birds being detected and in the apparent distribution of directions of the bird echoes. It seems probable that similar radar adjustments have affected the results of migration studies by other investigators since most studies which have employed medium and high powered surveillance radars have been done while the radars were simultaneously being used for other purposes.

These day to day variations in the sensitivity of various individual radars are important in view of (i) the extensive use of such radars for investigation of migratory behaviour, (ii) the increasing importance of radar in attempts to reduce the number of bird-aircraft collisions (Kuhring and Gunn, 1964; Flock, 1968; Gunn and Solman, 1968; Hild, 1969; 1970; Blokpoel, 1970a,b,c, 1971; Ferry, 1970; Jackson and Fiedler, 1970; Keil, 1970; Richardson, 1970; Myres and Cannings, 1971; Richardson and Gunn, 1971; Spiers et al., 1971), and (iii) the prospects for use of radar censusing in conservation and game-bird management (Bellrose, 1968; Myres, 1969; Flock and Bellrose, 1970).

This paper describes the radar adjustments and changes in flight behaviour that have been found to affect the bird detection capabilities of several radars in eastern Canada. It evaluates the severity of these effects, and suggests approaches to overcoming them.

METHODS

Tests on an ASR-5 radar

On a number of nights during October, 1969 I made systematic series of adjustments on an ASR-5 radar at Halifax International Airport, Nova Scotia, Canada (44°53'N; 63°30'W). The ASR-5 is a relatively low-powered (400 kilowatt) S-band* radar designed for short and medium range (0-60 n.mi.) air traffic control. Because of its short pulse duration (0.333 microsec.), the ASR-5 has relatively high resolution for a surveillance radar. It uses a parametric amplifier, multiple modes of Moving Target Indicator (MTI) and Sensitivity Time Control (STC) circuitry, a video integrator, and pulse staggering. Two supposedly identical transmitters and receivers are alternated between operational and stand-by use. Many birds are detected at ranges of ½-5 n.mi., but only a few large flocks are visible beyond 10 n.mi. Other features of the radar are given in Table 1 and in Anon. (1969).

The radar settings during 'normal' operation were 400 kW peak power output, vertical polarization, STC and Fast Time Constant (FTC) circuitry not in use, and MTI mode 'Two cancellers in series without feedback'. The following changes from the 'normal' settings were made one at a time:

(i) 350 rather than 400 kW peak power

(ii) 450 rather than 400 kW peak power

(iii) Circular rather than vertical (linear) polarization

(iv) FTC 1 in use rather than off (time constant = 2 µsec.)

(v) FTC 2 in use rather than off (time constant = ½ µsec.)

(vi) MTI mode '35 db Sub-clutter visibility' (two cancellers in series with feedback) rather than two cancellers without feedback.

In addition, observations and photographs were occasionally made with other changes from the normal settings:

(vii) STC in use rather than STC off

(viii) other MTI modes (single canceller, or two cancellers with different

---

* X, C, S, and L band radars are those using energy with wavelengths of approximately 3, 5, 10, and 23 cm respectively.

amounts of feedback) besides two cancellers without feedback The radar parameters and circuitry mentioned above are discussed below and in Barton (1964), Eastwood (1967), or Nathanson (1969).

The bird display resulting from the various radar settings was recorded by making one 35 mm still photograph of a Plan Position Indicator (PPI) display for each of several radar settings each night. It was not possible to make tests at all settings every night. The PPI was set to show an area with radius 10 n.mi. (18.5 km), and a single revolution (4 sec.) was recorded on each frame of film. The MTI circuitry was always used because of the extensive ground clutter present on the normal video display (Fig. 5A). Except for the tests of the effect of changing the mode of MTI, the double cancellation without feedback mode was always used. Tests were not done when ground-clutter was breaking through the MTI circuitry nor when cloud or rain echoes were present. The display and camera settings were not changed within the series of photographs on any single night. There was no significant or consistent change in migration density during each series of observations because (i) the entire series of adjustments and photographs could be made within five minutes, (ii) the observations were made well after the rapid early-evening increase in the number of migrating birds, and (iii) the order of the adjustments on a given night was randomized.

The negatives were developed and printed by a commercial photofinisher using continuous processing and printing techniques, thereby minimizing any possibility for variations in processing to influence the number of bird echoes visible. The bird echoes in each of 48 areas of the display were counted on each print; the 48 areas were defined by three distance categories (1-3, 3-5 and 5-7 n.mi.) and 16 azimuth categories ($0-22\frac{1}{2}^\circ$; $22\frac{1}{2}-45^\circ$; ... ; $337\frac{1}{2}-360^\circ$).

The mean direction of migration was determined by a combination of three techniques: (i) 'afterglow tails' on the bird echoes visible on the ASR-5 (see Fig. 7 and Eastwood, 1967:33); (ii) evaluation of the directions of streaks produced by the bird echoes on several-minute time exposures of the ASR-5 display (Fig. 2); and (iii) time-lapse film of the display from another radar, an AASR-1 (see below), operating simultaneously at the same site. For an analysis of the effects of radar adjustments on the apparent density of migration, the original counts in the 48 sectors of the display were reduced to three values per print--the total number of targets in the 1-3, 3-5, and 5-7 mile areas in the $67\frac{1}{2}^{o}$-wide areas centred on the mean bird direction and its back azimuth. The counts in the two $112\frac{1}{2}^{o}$-wide areas centred on the axis perpendicular to the mean bird direction were not used in this analysis. Many targets in the latter areas were suppressed by the MTI because of their low radial speed (see below). The nightly counts with the various changed settings were compared with the counts in the same areas of the display with 'normal' radar settings using one-tailed Wilcoxon matched-pairs signed-ranks tests (Siegel, 1956). One-tailed as opposed to two-tailed tests were appropriate because the direction of each effect could be predicted.

The counts in the same 48 sectors of the display were also used in analyses of thinning and dynamic range of the MTI. 'Thinning' refers to the decline in the density of bird echoes with increasing distance from the centre of the PPI display (Nisbet, 1963). For these analyses, only the photographs taken with 'normal' radar settings were used, and data were included from nights when no tests of the effects of radar adjustments were made.

Tests on an AASR-1 radar

On the nights of 12, 14, 15, and 16 May 1970 I made another series of tests, this time with an AASR-1 radar at Moncton, New Brunswick, Canada (46°05'N;

64°40'W). The AASR-1 is a medium-powered (550 kW) L-band surveillance radar used for long range air traffic control in many areas of Canada (Anon., 1956). AASR-1 radars were used by Blokpoel and Desfosses (1970) at Calgary, Alberta; by Richardson and Haight (1970) at Toronto and London, Ontario; by Richardson and Gunn (1971) at Edmonton and Calgary, Alberta and at Regina, Saskatchewan; and by Spiers et al. (1971) at Fort William, Ontario. Many birds are detected at ranges of 2-25 n.mi., and large flocks are regularly seen at 50 n.mi. or more. The AASR-1 has moderate resolution and two separate transmitting and receiving channels. The design is less complex than that of the ASR-5. There is a single MTI canceller without feedback, only one STC mode, and no pulse-staggering capability. Other performance details are given in Table 1 and in Anon. (1964a).

The radar settings which I considered 'normal' and against which comparisons were made were MTI on, horizontal polarization, STC and FTC not in use, and Instantaneous Automatic Gain Control (IAGC) off. The following changes from the 'normal' settings were made one at a time:

(i) STC on rather than off

(ii) FTC 1 on rather than off (time constant = $1\frac{1}{2}$ µsec.)

(iii) FTC 2 on rather than off (time constant = $\frac{1}{5}$ µsec.)

(iv) Circular polarization rather than horizontal (linear) polarization

Four series of 35 mm still photographs of the PPI display (30 n.mi. radius) were made on each of the four nights, with one photo taken with each setting during each series. Because some ground clutter was visible on the display even though MTI was always in use, I made 3-minute time exposures at each setting rather than exposures of single sweeps. Thus each bird echo left a short streak on the negative (Fig. 4). These streaks could be distinguished from ground clutter more readily than could the point echoes visible on single-sweep photos of the display. Because the observations were made during the middle of the night when changes in bird density were very gradual, and because the order of the settings in each series was randomized, there were no significant or consistent changes in density during the course of a single series.

The streaks produced by bird echoes were counted in the areas within 45° of the axis of the mean direction of migration (ie., not in the so-called MTI wedges where few birds were visible). Separate counts were made for the distance categories 10-15, 15-20 and 20-25 n.mi. Usually the streaks could not be counted at less than 10 n.mi. because of ground clutter and overlapping, and on one night they could not be counted in the 10-15 mile area either. Any streak which crossed the edge of a given sector was included in the count for that area if more than half of its length was within the sector. The four series of data each night were taken at intervals of about 40 minutes, so that a target would not be in the same sector in more than one series. Hence it was possible to treat the four series from a single night as independent data.

The film development and statistical procedures were the same as used for the ASR-5 tests.

Tests on an ASR-7 radar

On seven days in the period 19 October-1 November 1971 I tested the bird detection capabilities of an ASR-7 radar at NASA/Wallops Station, Virginia (37°57'N; 75°27'W). The ASR-7 is a very modern but rather low-powered S-band radar; it is similar to the ASR-5 in purpose, parameters, and capabilities*. The ASR-7 differs from most surveillance radars in that it has digital rather than analogue MTI and video integration. Nathanson (1969) discusses these digital systems. The ASR-7 also has a logarithmic receiver as well as the usual linear receiver.

On each of the seven days I made a series of photographs of the PPI display as various radar adjustments were made. On each day moderate-density migration of strong flock-type echoes was occurring. Extensive duck and goose migration was in progress at the time. The tests were done in the late morning or early afternoon. Each photo showed a single sweep of 4.6 seconds duration. MTI was always used. The following adjustments were made one at a time:

(i) STC on rather than off

(ii) Circular rather than linear polarization

(iii) Logarithmic rather than linear receiver

(iv) Video integrator off rather than on (The video integrator is called an 'MTI enhancer' on the ASR-7; it is a digital system)

(v) Various modes of MTI (single canceller; double cancellers without feedback; double cancellers with various amounts of feedback)

---

* Manufacturer = Texas Instruments; Wavelength = 10.8 cm; peak power = 450 kW; prf = 1200; 6-pulse staggering; first blind-speed = 126 kts (during unstaggered operation); pulse duration = 0.833 µsec; Scanning rate = 13 rpm; csc^2 beam pattern; multiple modes of STC and MTI; parametric amplifier. As on the ASR-5, only a few large flocks are visible beyond 10 n.mi. range.

The ASR-7 photographs were not analyzed by counting echoes; instead the apparent densities of migration were compared by eye.

Incidental observations with various radars

I have studied migration at two Air Traffic Control and three military radar sites in Nova Scotia and New Brunswick, Canada during 1969-1971. During the course of these observations I have frequently observed and photographed surveillance radar displays immediately before and after known types of radar adjustments were made. I have also made similar observations with high-powered nodding height-finder radars at the three military sites in the Maritimes. Eastwood (1967:197) describes such height-finding equipment. The changes in the apparent density (or lack of such changes) when these radar adjustments were made are discussed below. Details about the characteristics of the individual military radars are classified. However they are typical of the long-range military radars used in Canada and the United States (Corddry, 1957; Anon., 1965).

RESULTS AND DISCUSSION

The results of the ASR-5 and AASR-1 tests are shown in Table 2 and in Figures 1 and 3 respectively; one representative series of the test photographs from each of the radars is shown in Fig. 2, 4 and 9. The variations in detectabilit of birds as revealed by these tests, by my incidental observations of various radars, and by the literature are considered under the following main headings: transmitter power output, properties of the beam, receiver properties, channel changes, display settings, and digitized radar data. While I will frequently refer to the effects of radar adjustments on the apparent migration density, the results are equally applicable to radar studies of local non-migratory movements.

Transmitter power output

A decrease in the ASR-5 power output from 400 kW to 350 kW produced a very small but consistent and statistically significant ($P < .05$) decrease in the number of targets detected (Fig. 1 and 2; Table 2). At various ranges the decrease averaged 6 to 10 per cent. Likewise, an increase from 400 kW to 450 kW produced a small but consistent and significant increase in the number detected averaging 4 to 16%.

The only comparable data that I know of are found on Plate 22 of Eastwood (1967). Counts of 'angels' on that plate indicate that an increase in power output by a factor of two (far larger than occurs during normal operation) increases the apparent number of bird targets by less than 60%.

When evaluating the importance of changes of a few percent in the number of bird targets being detected, it is important to recall that the amount of migration frequently varies between nights over a range of two and occasionally three orders of magnitude (Newman and Lowery, 1964; Nisbet and Drury, 1968:502; Blokpoel, 1970b; Richardson, unpubl.).

In actual practice, day to day variations in the ASR-5 power output are over a narrower range than my tests. In a 30 day period, the power was never observed to be outside the range 385-410 kW when checked each day after about 15 hours without adjustment. The tolerable range for ATC purposes is 385-425 kW (Anon., 1969:59). I have made observations of similar day to day consistency in power output from several other radars.

The basic radar equation,

$$r_{max} = \sqrt[4]{(P_t G^2 \lambda^2 A)/(64\pi^3 P_m)}$$

where r_{max} = maximum detectable range of the target

P_t = the transmitted power

G = the antenna gain

λ = the wavelength of the radiation

A = the radar cross-sectional area of the target

P_m = the minimum detectable power for received echoes

indicates that r_{max} for a given target varies as the fourth root of the transmitted power. Hence a change in power output of a few percent should produce very little change in the maximum range at which a given target can be detected. This prediction, the test results, and the observed consistencies of the power outputs of various radars together suggest that variations in power output are not ordinarily a significant source of error when estimating the density of migration (but see the section on channel changes below).

Properties of the beam

Polarization.— The energy radiated from a surveillance or nodding height-finder radar antenna is normally polarized in either the horizontal or the vertical plane. Radiation polarized in either of these planes is said to be linearly polarized. Such radars usually can be switched to circular polarization, which is often used for detecting aircraft in the presence of echoes from rain, snow or cloud (Raverdy, 1962; Eastwood, 1967:15). With near-spherical targets such as water droplets, circular polarization has an effect identical to a drastic reduction of the Radar Cross-Section (RCS). The RCS is a measure of the amount of energy reflected by the target. Circular polarization reduces the apparent RCS of rain and snow by 15-30 db, but it also reduces the apparent RCS of aircraft by about 5 db (Nathanson, 1969:146). If one regards the aircraft echo as the desired signal and the weather echo as noise, then in the presence of weather echo, circular polarization gives a better signal to noise ratio than linear polarization. Therefore within weather echo it is easier to detect an aircraft using circular polarization. However, when using circular polarization the absolute value of the power received from an aircraft is reduced from that received with linear polarization. Hence with circular polarization the maximum range at which detection is possible is reduced from that with linear polarization and no weather echoes.

The RCS of at least a few birds is affected by the plane of polarization (Houghton, 1969). Hence one would predict that as with aircraft, the apparent RCS of birds would not be reduced as drastically by circular polarization as would the RCS of weather targets. My tests and observations confirm this.

When the ASR-5 and AASR-1 radars were switched from linear to circular polarization, the number of bird targets being detected decreased an average of 11 to 54%, depending on the radar and range (Table 2). On these and other radars this difference is equal to ½ to one unit on a 0 to 8 ordinal scale that I use for recording the volume of migration (Fig. 6). The ASR-7 is the only radar that I have encountered which shows as many birds with circular as with linear polarization (Fig. 9). While circular polarization significantly reduces the number of bird echoes detected at all ranges on most radars (Figures 1-5 and Table 2 plus incidental observations of other radars), it is frequently possible to detect birds using circular polarization when with linear polarization they are completely obscured by weather echoes.

The preceding paragraphs consider the effects of a change from linear to circular polarization. However switching between the two types of linear polarization, vertical and horizontal, may also have an effect on the number of birds being detected. According to the ellipsoidal model proposed by Schaefer (1968:66), when birds having weights less than about 45 g are viewed from the side with a 10 cm (S-band) radar, they should have a larger RCS with horizontal than with vertical polarization. Schaefer's model predicts that with a 23 cm (L-band) radar the RCS will be larger with horizontal than with vertical polarization for birds with weights less than about 550 g. Even wi an S-band radar the majority of the migrating birds would usually be below this weight limit. Hence one would predict that in cases when birds were flying individually rather than in flocks (or in the case of an L-band radar even if they were flying in small flocks), more echoes would be detected wit horizontal than with vertical polarization, other factors being equal.

On a few nights I have been able to observe the display of a high-power L-band surveillance radar immediately before and after it was switched from horizontal to vertical polarization (or vice versa). In each case the appar bird density was, as predicted, slightly less with vertical than with horiz polarization. The difference was perhaps equal to ½ a unit or at most one on the 0 to 8 scale. Thus for ornithological purposes it is fortunate that AASR-1, ASR-5 and ASR-7 radars (and most others) can each operate with only orientation of linearly polarized energy (Table 1).

Vertical performance diagram (VPD).--The VPD of a surveillance radar shows distance and height ranges within which targets with various radar cross-se can be detected (see Eastwood, 1967:20).

The VPD is largely determined by the gain of the antenna for various elevation angles. The antenna gain is a measure of the degree to which the antenna concentrates the radar energy. The gain of a long-range search radar is maximal at a low angle above the horizon, usually in the range $\frac{1}{2}^{\circ}$ - 2°, and it decreases above and below this angle. It generally decreases much more rapidly at angles less than that of the maximum gain than it does at angles greater than that of the maximum. Nevertheless, very little energy is directed to elevation angles of more than 25°. On one pair of tests, the power radiated at 25° above the horizon was -12 db on an ASR-5 and -14 db on an AASR-1 compared to the power radiated towards the elevation angle with maximum gain. Hence, when observing birds within a few miles of the radar site, as one frequently does with lower-powered surveillance radars like the ASR-5, the higher flying birds are less likely to be detected. Using a radar similar to the ASR-5, Steidinger (1968:215) has noted that birds within about 4 n.mi. of the site are not detected when they are flying more than several hundred metres above the ground. The average height of migration varies widely between days. In Nova Scotia and New Brunswick I frequently observe movements with a modal altitude of 200-600 m, but on rare occasions the modal altitude has been as high as 4000 m. On most occasions there are a few individual birds at 2000 m or more. Thus the same number of birds with the same RCS distribution flying at different heights on different days could give very different apparent migration densities if examined at short range. Fortunately, the birds which produce most of the high targets (waterfowl, shorebirds) tend to fly in flocks and hence are less likely to be missed than smaller targets might be.

At long ranges it is the low-flying rather than the high-flying birds that are not detected. I have made a series of simultaneous observations over relatively flat terrain with high-powered surveillance and nodding height-finder radars. By measuring the heights of the targets visible on the PPI, I found that the height distribution of the bird echoes detected by the surveillance radar at 20-30 n.mi. was not different from that for the birds detected at 10-20 n.mi. Beyond 30 n.mi. range, the number of targets visible below 300 m began to decrease. When bird echoes were visible on the PPI at ranges of 50 n.mi. or more, they were invariably above 600 m. These results are consistent with predictions derived from the range of the radar horizon (Nathanson, 1969:221).

Unfortunately, when the terrain is not flat the distance of the radar horizon is more difficult to estimate and it varies with azimuth. This results in 'shadowing' by hills. Thus a bird with a given RCS flying at a low elevation angle may not be detected if it is on one azimuth but will be detected when at the same altitude and range on other azimuths. Harper (1958:485), Adams (1962), Myres (1963:36), Nisbet (1963:440), Drury and Nisbet (1964:72), and Steidinger (1968:198) have reported reductions in the apparent density of migration on certain azimuths because of such shadowing effects, and I have observed the same phenomenon on various radars in Canada.

Several studies have shown that bird movements may occasionally be underestimated or even undetected because the birds are flying very low (Sutter, 1957a; Lack, 1959; Mascher et al., 1962; Axell et al., 1963; Gehring, 1963; Lee, 1963; Myres, 1964b; Wilcock, 1964,1965; Evans, 1966). It is clear that the apparent bird density will be less affected by variations in the height distribution and by shadowing the closer to the site that it is measured (with the exception that at ranges less than about 5 n.mi. some high-flying birds are likely to be missed). Also, the closer to the site that the density is measured, the less will be the effect of variations in the RCS distribution and radar performance on the apparent density.

Some modern surveillance radars have several 'stacked' beams, each responsible for coverage of a narrow range of elevation angles (Barton, 1964:6, 256). Echoes returning from the various beams are detected by separate receivers, and the receiver outputs are then superimposed onto a single PPI. The various receiver adjustments described below can be made independently on each of the receivers. Therefore the Vertical Performance Diagram and thus the degree of suppression of bird echoes can change considerably from time to time. I have found that such day to day variations can have a drastic effect on the apparent density. On some occasions, birds are completely invisible or else are invisible within some range because of adjustments made on the receivers for one or more low-angle beams.

When studying migration with a stacked-beam radar, I use 'raw video' whenever it is available. The raw video is obtained by extracting the signals from each receiver before they are modified by MTI, STC, FTC, etc., and then combining the signals from each receiver with equal weights applied to the various beams. Thus one can avoid many of the sources of day to day fluctuations in sensitivity. Unfortunately, uncancelled ground clutter is present on the display when raw video is used.

Anomalous propagation (AP).--Under certain atmospheric conditions the radar beam is bent downwards more than usual (Eastwood, 1967:51). Some of the radar energy may be trapped in a 'duct' near the surface, an effect comparable to increasing the antenna gain at low elevation angles. Therefore under conditions of AP birds flying at a given height are often visible at greater range than usual. This is another factor contributing to the large day to day variations in the detectability of birds at long range. Since surveillance radars apparently can detect low flying birds fairly well out to ranges of about 30 n.mi. (see above), AP should have little effect on the apparent density at ranges less than 30 n.mi.

AP also produces ground echoes at much greater range than usual. When properly adjusted MTI circuitry is used to suppress ground clutter, this is usually not a serious problem (but see the section on MTI dynamic range limitation below). However, when normal video, raw video or poorly adjusted MTI video is used, AP can sometimes produce ground echoes over such a wide area that it is difficult to detect birds and almost impossible to measure the density and direction of migration.

Pulse volume.--The pulse volume is determined (i) by the pulse duration, and (ii) by the vertical and horizontal beamwidths at the range in question.

Radar beams often do not have sharp, well-defined edges. The beamwidth is usually quoted as the angle between the points at which the radiated power is $\frac{1}{2}$ that in the centre of the beam. The effective beamwidth, the angular width within which the target produces an echo large enough to be detected, is unlikely to be the same as the $\frac{1}{2}$-power beamwidth. It depends on three characteristics of the target: (i) the radar cross-section (the larger the RCS, the farther the target can be from the axis of the beam while still giving a detectable echo), (ii) the range (the greater the range, the closer a given target must be to the centre of the beam to give a detectable echo), and (iii) the azimuth (shadowing by hills can reduce the effective beamwidth beyond the hills). For a target with a given RCS at a given range and azimuth, the effective beamwidth is also dependent on changes in receiver sensitivity and in power output. Thus, while the beamwidth as defined by the distance between the half-power points increases with range, the effective beamwidth is also affected in a complex way by various other factors. Hence it is very difficult to predict the pulse volume and therefore the resolution of a surveillance radar or nodding height-finder for given bird targets. Imprecise knowledge of the beamwidth and resolution is not an important problem when estimating the number of bird targets in a light or moderate migration, or when using an ordinal density scale such as my 0-8 scale. However it is a serious limitation when trying to estimate the actual number of targets involved in a dense migration, especially if the beam is stationary (see Able, 1970b and Blokpoel, 1970b). Blokpoel (1971) describes an attempt to compensate for the problem.

Some radars can operate with various pulse durations. The shorter the pulse, the smaller the pulse volume and the higher the resolution. The shorter pulse length of the ASR-5 (0.833 µsec) compared to the AASR-1 (2 µsec.) permits much better resolution of dense passerine migrations into separate targets. Thus it is easier to make echo counts on the ASR-5 than on the AASR-1. The ASR-5 occasionally shows waterfowl flocks as non-point targets (ie., targets extending over an area larger than the horizontal dimensions of the pulse volume); the AASR-1 very rarely resolves bird echoes into non-point targets.

On the other hand, the shorter the pulse duration on a radar operating at a given pulse repetition frequency and peak power, the lower the pulse energy and hence the shorter the range capability on a given target. Furthermore, when observing very dense movements, the shorter the pulse, the smaller the pulse volume and hence the fewer birds and the smaller the total RCS per pulse volume. Bellrose (1964:129) and Gauthreaux (1970:17) have both reported that the WSR-57 weather radars detect birds better when using a long pulse duration than they do with a shorter duration.

Properties of the receiver

Type of receiver.--The most common form of radar receiver is the linear receiver. In this system the video voltages are directly proportional to the received signal amplitudes. Some radars have a logarithmic receiver as well as a linear receiver. When a log receiver is used, the video voltages are proportional to the logarithms of the signal amplitudes. Other specialized types of receivers may be found on military radars where they are used in anti-jamming applications.

Unless otherwise noted, all results discussed in this paper were obtained using linear receivers. However when the log receiver of the ASR-7 was tested it was found to detect about as many birds as the linear receiver (Fig. 9). The excessive noise present in the ASR-7 log video is the result of non-optimal adjustment rather than of any inherent property of log receivers.

Tuning.--Tuning means matching the frequency to which the receiver is sensitive with the frequency of the transmitted radar energy. On several occasions after I had noticed that birds were not being detected as well as usual, it was discovered that the receiver was improperly tuned. Such occurrences are rare. On a well-maintained surveillance radar, improper tuning is normally discovered and corrected rapidly since the problem is usually apparent even when looking for aircraft.

Noise figure.--The noise figure of a receiver is a measure of the noise generated within the receiver, as opposed to the noise received from the outside. Eastwood (1967:82) indicates that the noise figure should be very constant on a modern radar. However during normal operation of the Halifax ASR-5 I have recorded fluctuations of its noise figure meter from 1 db to $4\frac{1}{4}$ db (usually $1\frac{1}{4}$ - $3\frac{1}{4}$ db). The specified standards for this radar are a normal operating range of 1-2 db and a maximum permissible value of $4\frac{1}{4}$ db (Anon., 1969:15,30). Dr. F.R. Hunt of the Radio and Electrical Engineering Division, National Research Council of Canada, has indicated (pers. comm.) that on radars with parametric amplifiers the noise figure can drift unless excellent design precautions are taken. The ASR-5 has a parametric amplifier. On the other hand, Dr. Hunt points out that noise figure meters can be subject to errors that appear as noise figure drift even if the nois figure is constant.

Since (i) variations in the ASR-5 noise figure over a 3 db range may be occurring, (ii) the minimum detectable signal (MDS) varies with the noise figure, (iii) a change of x db in the MDS has the same effect on detection ability as a change of x db in transmitted power, and (iv) my ASR-5 tests show that a change in transmitted power by only ½ db produces a slight but consistent and statistically significant change in the number of bird targets detected (see above), I conclude that temporal variations in the receiver noise figure may produce significant changes in the apparent bird density. Summing over all the tests, 14% more echoes were detected in the 1-5 n.mi. area with 450 kW than with 350 kW. Since this is a difference of 1.1 db in the power output, one would predict that a change in the noise figure from 4 to 1 db would increase the number of detected echoes in the 1-5 n.mi. area by at least 30%.

IF Gain.--At most installations, the gain of the intermediate frequency (IF) amplifier appears to be changed infrequently. However, observations of the Halifax AASR-1 display were made on several occasions when the IF gain was adjusted by the radar technicians upon request from the Air Traffic Controllers. These adjustments produced slight but noticeable effects on the apparent bird density; the differences were never more than one unit on the 0-8 scale of migration densities mentioned above.

Sensitivity Time Control (STC).--At close ranges, high sensitivity is not needed to detect large targets such as aircraft, and often it hides the aircraft amidst echoes from undesired targets such as birds. STC counteracts this problem by reducing the gain of the IF amplifier by an amount inversely related to the range (Anon., 1969:8; Nathanson, 1969:111). On the surveillance radars which I have used there is no gain reduction beyond 20 or at most 30 n.mi.. On weather radars the gain reduction is often more severe and extends to greater range. The STC can be switched off when not needed. It was never used on the Halifax AASR-1 when I was using that radar to study migration. However, STC is used frequently on the Halifax ASR-5 and on some military radars.

The STC circuits on all radars that I have examined markedly reduce the number of birds visible near the centre of the display. Only a few very large bird targets are visible on the ASR-5 or ASR-7 when any of the STC modes is in use (Fig. 9), and none of the passerine echoes normally visible within 5 or 6 n.mi. of the site are visible when STC is switched on. On the AASR-1 radars, STC does not have nearly as severe an effect. This is no doubt partially because the AASR-1 can detect birds at ranges where the STC produces little or no gain reduction (Fig. 3 and 4; Table 2). The tests on the Moncton, N.B. AASR-1 reveal a 40% decrease in the number of bird echoes visible at 10-15 n.mi. when STC is turned on, but no decrease at 15-20 n.mi. On high-powered military surveillance and height-finding radars, STC produces a noticeable reduction in the number of bird echoes detected at close range, but even the passerine movements are readily detected at ranges greater than that beyond which the STC has no effect.

Steidinger (1968:216) has reported that STC can suppress bird echoes close to his radar in Switzerland. Mulholland and Soden (1967) have reported the use of STC to suppress 'angels' (no doubt mainly birds) that appear on the displays of Australian radars. Air Traffic Controllers commonly use STC to suppress 'clutter' resulting from birds.

Fast time constant (FTC).--The echo pulse from a point target (such as an aircraft or a bird) should have about the same duration as the transmitted pulse, whereas returns from the ground and from cloud or rain may be many pulse widths in duration. FTC circuits are not supposed to affect short echo pulses, but they suppress all but the leading edge of the prolonged returns coming from large areas of clutter (Nathanson, 1969:112). The time constant of an FTC circuit is the length of time during which an echo is permitted to pass before suppression begins. Two FTC circuits are found on both the AASR-1 and the ASR-5 radars. The two circuits differ in the length of their time constants.

Both FTC circuits on both radars reduced the apparent migration density statistically significantly (Fig. 1-4; Table 2). However, with the exception of the 5-7 n.mi. area on the ASR-5, the reduction was slight--much less than one unit on the 0-8 density scale.

During the ASR-5 and the AASR-1 tests, there were no occasions when the display was saturated with bird echoes. When observing very dense migrations on other radars, I have noticed that FTC had a more pronounced effect. When FTC was switched on solid masses of bird echo resulting from passerine movements denser than the resolution capability of the radar were broken up into small discrete echoes separated by narrow areas showing no return. This effect was particularly pronounced when FTC was used in conjunction with logarithmic receivers (see above and Nathanson (1969:112). The reduction at high migration densities was one and sometimes even two units on the 0-8 scale.

I conclude that at low and moderate bird densities (and even at fairly high densities when using high resolution radars, Fast Time Constant circuitry has little effect on the apparent migration density. However, at high densities it can reduce the apparent density considerably. Fortunately, with the exception of its use in logarithmic receivers, FTC is in my experience almost never used on most radars. It was not used on the Halifax AASR-1 during my observation period.

A more complex circuit called a Pulse Length Discriminator (PLD) is used instead of FTC on some radars (Nathanson, 1969:116). The effects of a PLD on the apparent bird density are unknown, but are probably similar to those of FTC. PLD circuits are frequently used on radars in Britain (Hunt, pers. comm.).

Instantaneous Automatic Gain Control (IAGC).--When IAGC circuitry is used, the gain of the IF amplifier at any instant is inversely related to the average power received during several pulse durations prior to that instant. Thus the detectability of well-separated point targets is, at least theoretically, only slightly reduced while large areas of clutter are suppressed (Nathanson, 1969:111) One would predict that IAGC would have little effect on the apparent bird density during light and moderate migration when the bird targets are well separated. However during dense migration, when there are bird echoes from most or all pulse volumes, the apparent density would probably be reduced because of a lower average level of the IF gain.

The AASR-1 has IAGC circuits in both the Normal and MTI receivers; the ASR-5 has IAGC in only the Normal receiver. While no systematic tests were done, occasional observations during periods of light and moderate migration using the Moncton AASR-1 showed no obvious reduction in the apparent migration density when IAGC was switched on (Fig. 4). It is possible that the circuit at Moncton was not operating properly. IAGC was never used on the Halifax AASR-1 during my observation periods.

Some radars have a more sophisticated type of IAGC system referred to as Constant False Alarm Rate (CFAR) circuitry (Nathanson, 1969:133). My observations of a military surveillance radar indicate that CFAR has little effect on the apparent density of light and moderate migration. However on some occasions it reduces the apparent density of dense migration by one or two units c the 0-8 scale. On other occasions, there is little or no obvious effect on high-density migration, presumably because of temporal differences in the adjustment of the CFAR system.

Video integration.--Most surveillance radars, including the AASR-1, ASR-5 and ASR-7, are equipped with video integrators. Prior to 1966 or 1967 the AASR-1 radars in Canada did not have them. These devices combine the received signals from each pulse volume over several pulses, thereby improving the signal to noise ratio by several db. This is possible because on surveillance radars the beamwidth and antenna rotation rate are such that a given point target is illuminated for several successive pulses during each scan. However, the PPI display is also a form of video integration device since the returns from a number of pulses are added together in producing a spot at any point on the PPI. For most applications the PPI is about as effective as an electronic integrator (Nathanson, 1969:103), and when an electronic integrator is used with a PPI the S/N ratio may be reduced rather than increased (Barton, 1964: 177).

While no systematic tests were done, the video integrator of the ASR-5 seemed to have little effect on the apparent bird density. If anything, there was a slight decrease when it was switched on, but this was much less than one unit on my 0-8 scale. The distribution of migration intensities recorded during September and October 1965 using the Halifax AASR-1 without an integrator was slightly lower than that recorded using the same radar with an integrator during the same months in 1969 (3/4 of a unit difference in the medians using the 0-8 scale). However this difference could easily have resulted from factors other than the addition of a video integrator.

Most video integrators are analogue devices that operate by adding or subtracting voltages. However the ASR-7 has digital integrators. The digital integrator in the MTI system of the ASR-7 improved the display very noticeably, in contrast to the analogue integrator on the ASR-5. As shown in Fig. 9, the digital integrator on the ASR-7 markedly reduced the amount of noise, thereby making birds more obvious.

In my experience the video integrator on an individual radar is either always used or else almost never used. Hence video integration is not normally a possible source of temporal variations in radar sensitivity.

<u>Coherent Moving Target Indicator (MTI)</u>.--Most surveillance radars are equipped with coherent MTI circuitry. Its purpose is to suppress the echoes from stationary targets while producing minimal effect on moving targets.

In order to detect aircraft or birds at long range, most of the radar energy must be directed at elevation angles below 5°. Hence energy is reflected from hills and other stationary surface objects as well as from airborne targets. This ground clutter is usually restricted to areas within 20 or 30 miles of the radar site unless there are high hills at somewhat greater range. During conditio of anomalous propagation (see above) ground clutter is detected out to longer rang than usual.

Birds and aircraft usually cannot be seen in areas of the display where uncancelled ground clutter is present. Since low and medium powered radars can ordinarily detect only large flocks at the ranges beyond which clutter occurs. one must on such radars use MTI to reveal the birds flying over and between the areas of MTI-cancelled clutter. High-powered radars can normally detect birds at ranges beyond those where clutter is a problem, but at such distances low flying birds are unlikely to be detected. Hence MTI is useful even on high-powered radars.

The MTI recognizes only the radial component of a target's velocity, and so targets moving tangentially (ie., with zero radial speed) are suppressed. In addition, the MTI also reduces the echo strength from targets moving at slow radial speeds and at speeds near various blind speeds. If the wavelength (λ) is given in cm and the time between successive pulses (T) in microseconds, the blind speeds in knots are $9700\lambda n/T$ where $n = 1,2,3, \cdots$. The blind speeds of the AASR-1 and ASR-5 are the integer multiples of 78 and 126 knots respectively. With the simplest and commonest form of MTI, the relationship between the radial speed and the amplitude of the target echo after processing by the MTI circuitry approximates a rectified sine curve (see Fig. 8, 'single canceller' curve) with the nulls at each blind speed. Barton (1964), Eastwood (1967), and Nathanson (1969) give further details.

Unfortunately, because of wind-blown trees, antenna motion, and small system instabilities, ground clutter has a narrow velocity spectrum of a few knots width centred around zero velocity. This makes it desirable to suppress targets with speeds below a few knots more strongly than the sine-curve response of a simple single-canceller MTI can manage. To do this, two cancellers are often used in series, giving a $\sin^2$ velocity response curve (Fig. 8). This double cancellation MTI suppresses low-speed targets well, but it has the disadvantage of reducing the response from targets with almost all radial speeds more than would a single canceller. To increase the response at most radial speeds while retaining strong cancellation of low-speed targets, feedback circuits are often added to a double-cancellation MTI (Fig. 8). Furthermore, pulse-staggering techniques can be used to minimize but not eliminate target suppression at most blind speeds. Barton (1964) and Nathanson (1969) discuss these more sophisticated forms of MTI circuitry.

Some modern radars such as the ASR-7 have digital rather than analogue MTI systems. In these radars the signals are converted to digital data, processed to suppress non-moving targets, and then converted back to analogue data for display on a PPI in the usual manner. The digital MTI system of the ASR-7 does exactly the same operations on the signal as the analogue MTI of the ASR-5; hence one would expect similar effects on the bird display. This proved to be the case.

The effects of MTI systems on the display of bird targets are complex and variable. While it would therefore be desirable not to use MTI, for the reasons given above it is frequently necessary in surveillance radar studies of migration. The following sections discuss the known and suspected effects of MTI on the bird display.

The best-known effect of coherent MTI circuitry on the bird display is the production of 'MTI wedges' (Sutter, 1957a,b; Gehring, 1963; Nisbet, 1963; Drury and Nisbet, 1964; Eastwood, 1967:57; Steidinger, 1968). When there is little variation in the directions of movement of the bird targets, all targets crossing the azimuths perpendicular to the mean direction have little or no radial velocity and hence are suppressed by the MTI. This produces a pair of wedge-shaped areas wherein few birds are detectable. With a unimodal distribution of bird flight directions having given variance, the angular width of the MTI wedges should theoretically depend on:

(i) The power output and sensitivity of the radar. The greater the power or sensitivity, the greater the signal to noise ratio of the echo from a given target at a given range and hence the slower the radial speed necessary for the MTI to reduce the S/N ratio below the detection threshold. Besides the usual determinants of receiver sensitivity (see above), improper adjustment of the MTI circuits can also seriously reduce sensitivity.

(ii) The type of MTI in use. The shape of the velocity response curve will determine the minimal radial speed necessary to obtain a detectable return from a target with a given radar cross-section (RCS) and range.

(iii) The range of the bird targets. The greater the range, the smaller the return and hence the less cancellation required to reduce the return below the detection threshold.

(iv) The size distribution of the bird targets. The larger the RCS of a target, the greater the return at a given range and hence the slower the radial speed necessary for cancellation. The radar cross-sections of birds are not always directly proportional to their sizes (Konrad et al., 1967; Schaefer, 1968; Nathanson, 1969; Bruderer, 1969); this phenomenon is known as Mie-region fluctuation. Nevertheless, there is a general positive correlation between RCS and size. Hence if most of the birds flying on one occasion are larger than those flying on another, the MTI wedges are likely to be narrower in the former case. Since at least at X- and S-bands the RCS of most birds appears to be greater when they are viewed from the side than when viewed from the end (Edwards and Houghton, 1959; Bruderer and Joss, 1969; Houghton, 1969)*, the MTI wedges are likely to be narrower than would be predicted on the basis of the end-view RCS distribution.

---

* Nisbet (1963:459) has concluded that the RCS at L-band (wavelength about 23 cm) does not vary with aspect. Because his conclusion is based on comparisons made within 40° of end-view, it may not apply to the end vs side comparison. While to my knowledge there have been no direct measurements of RCS polar diagrams using L-band radars, Schaefer (1968) has concluded from theoretical considerations that the cross sections of birds in both the Rayleigh and Mie regions (which include all birds at L-band) are less at end than at side view.

I have frequently examined the normal video displays (ie., MTI not in use) of both L and S band radars. Birds are usually visible to greater range when viewed from the side than when viewed end-on. This suggests that the RCS of birds at L as well as S band is indeed greater at side than at end view.

(v) The ground speed distribution of the bird targets. The greater the flight speed, the greater the radial speed at any azimuth except those exactly perpendicular to the flight direction. At low speeds, the greater the radial speed, the less the cancellation and hence the narrower the range of angles within which the S/N ratio is too low for detection. If the birds were flying fast enough such that on some azimuths their radial speeds were close to a blind speed, MTI wedges would also occur along those azimuths. Since the blind speeds of most radars are such that birds rarely if ever fly much faster than the first blind speed, the only likely position for a second pair of MTI wedges is perpendicular to the usual pair.

In summary, one would predict that the greater the power, sensitivity, target sizes, and target speeds, and the less the range of the targets, the narrowe would be the MTI wedges. The shape of the velocity response curve and the amount of variation in flight directions should also affect the wedge width.

While I do not have quantitative data suitable for testing most of the above predictions, my results tend to confirm some of them.

(i) With similar types of migration the MTI wedges are usually narrower on high-powered military surveillance radars using single-canceller MTI systems than on the medium-power AASR-1, which also has a single canceller.

(ii) When following large echoes that can be detected at long range and which doubtless originate from flocks, I usually find that they are undetected for only a few sweeps of the radar as they cross the tangential azimuth. In contrast, fine echoes of the type genera attributed to passerines are usually lost well before they reach the tangential azimuth. Since the large targets normally move faster than the passerines, these results are very likely due to both the target size and speed effects.

(iii) I have confirmed that the rate of azimuthal 'thinning' as one moves towards the azimuths of the MTI wedges depends on the range. For this analysis I used only areas from which no ground clutter was received; hence the MTI dynamic range problem discussed below was avoided. After correction of the raw data for random overlap (see Nisbet, 1963:458), I found that the ratio

$$\frac{\left[\text{Number of bird echoes visible within } 11^{\circ} \text{ of the azimuths perpendicular to the mean direction}\right]}{\left[\text{Number within } 11^{\circ} \text{ of the azimuth and back azimuth of the mean direction}\right]}$$

was about 2.3 times as large at 1-3 n.mi. as at 3-5 n.mi. This difference is statistically significant (P = .025) using a one-tailed t-test. These results confirm the range dependence of the severity of MTI suppression. They were based on data obtained during 18 nights in October 1969 with the Halifax ASR-5 using the 'normal' settings (as defined in the Methods).

(iv) The variation among the flight directions of different bird echoes visible at a given time can range from very little (standard deviation of less than 10°) to very great (nearly random distribution of flight directions). The MTI wedges are obvious and wide when there is little variation, less obvious when there is moderate variation, and absent when there is much variation.

<u>MTI suppression is not confined to the MTI wedges</u>, although the effects are most severe there. Arguments analogous to those above should apply to the degree of suppression outside the wedges. The greater the power, sensitivity, target sizes, target speeds* and angular distance from the axis of the MTI wedges, the fewer targets whose S/N ratios would be reduced

---

* with the exception that at radial speeds above the first optimum speed but below the first blind speed, the greater the speed, the fewer detected.

below the detection threshold by a given MTI system, and therefore the greater the apparent bird density. Variations in the velocity response curve between modes of MTI would again be expected to affect the proportion of targets suppressed and hence the apparent density. The greater the range, the smaller the S/N ratios of the echoes before cancellation and hence (i) the larger the proportion of echoes whose S/N ratios would be below the detection threshold after cancellation, and (ii) the larger the effect of changes in MTI mode and of variations in the distributions of target cross-sections and speeds on the apparent bird density.

If, for example, the smallest bird targets could be detected to a range of x n.mi. under good conditions (optimal radial speed; normal power output and receiver sensitivity), then at $\frac{1}{2}x$ n.mi. under the same conditions the power of the echoes received from these birds would be 12 db above the detection threshold (since $P \propto 1/r^4$). The power output and receiver sensitivity do not decrease by more than $\frac{1}{2}$ db and 2 db repectively from their normal values without maintenance procedures being initiated (see above). Hence even under suboptimal conditions of power and sensitivity the radial speed could decrease to a value which gives a $9\frac{1}{2}$ db reduction in the echo power at the output of the MTI before the birds would be undetected at a range of $\frac{1}{2}x$. For an MTI system using a single canceller without feedback, $9\frac{1}{2}$ db or more of suppression is produced when the radial speed is 11% or less of the first blind speed, or below 14 kts on the ASR-5 and ASR-7 and 9 kts on the AASR-1. If a double-cancellation without feedback MTI were in use, radial speeds of about 20% of the first blind speed would be required to assure detection at $\frac{1}{2}x$. Fortunately, most radars using double-cancellation MTI use it with feedback, thereby reducing the radial speed needed for detection.

Passerines frequently fly as slowly as 15 kts during local flights (Schnell, 1965). While during migration their average speeds as estimated visually (Meinertzhagen, 1955) and by radars not using MTI (Harper, 1957; 1958; Rinehart, 1966; Gehring, 1967; Bruderer, 1969, 1971; Richardson, unpubl.) are almost always above 15 kts, a small proportion of the individual migrants are often moving at slower speeds. There have been many other observations of the speeds of migrants using radars that either had MTI or else were not described in detail. In spite of the fact that these studies may have been biased by MTI in favour of faster birds, they often recorded migration at speeds not greatly in excess of 15 kts (Tedd and Lack, 1958; Adams, 1962; Gehring, 1963; Lack, 1963; Lee, 1963; Nisbet et al., 1963; Drury and Nisbet, 1964; Houghton, 1964; Casement, 1966; Steidinger, 1968; Parslow, 1969; Richardson, unpubl.). Thus one must conclude that when using MTI at ranges appreciably greater than $\frac{1}{2}$x, some migrants are undetected because of their slow speed.

Variations in ground speed will therefore affect the apparent bird density. Even at a range of $\frac{1}{2}$x some passerines are probably undetected when ground speeds are reduced by head winds* or when double cancellation MTI is used without feedback. With a given type of MTI, the bias in apparent density induced by speed variations will be more severe on radars with higher than on those with lower blind speeds. This occurs because the minimum speed at which a target with a given RCS can be detected is directly proportional to the lowest blind speed.

---

*Fortunately for purposes of estimating migration density, some birds seem to adapt their air speed to the wind speed and direction, thus maintaining a more constant ground speed than would be expected (Schnell, 1965; Bellrose, 1967; Bruderer, 1971; Tucker and Schmidt-Koenig, 1971). Nevertheless, ground speeds are normally somewhat lower with head than with tail winds (Steidinger, 1968:219; Bruderer, 1971).

Data suitable for testing the above predictions are scarce.

(i) Steidinger (1968) has reported that birds moving at less than 30 km/hr (16 kts) were not detected by his radar. The first blind speed of the radar he used was 82 kts. Thus birds moving at 20% or less of the first blind speed were suppressed. Unfortunately the type of MTI system used on this radar was not given.

(ii) My observations of the effects of changing the MTI mode on the Halifax ASR-5 and the Wallops Station ASR-7 showed definite changes in the apparent bird density, especially at long range (Fig. 7 and 9). The smallest number of birds was detected using double cancellation without feedback, an intermediate number was recorded with single cancellation, and the largest numbers were recorded with double cancellers plus feedback. I made more detailed comparisons of the apparent bird densities on the ASR-5 using the double cancellation without feedback and using the '35 db SCV' mode of double cancellation with feedback (Fig. 1 and 2; Table 2). Significant differences between the modes of MTI were confirmed at all ranges, but the difference became larger with increasing range. The differences between the MTI modes in the apparent density were, however, considerably less than one unit of the 0-8 scale in all but the longest (5-7 n.mi.) range category.

Thus when using MTI it would appear to be desirable to estimate migration densities by observing the number of targets at a range of perhaps $\frac{1}{4}$ or (1/3)x rather than $\frac{1}{2}$x. This would minimize the chances of missing slow targets. As discussed earlier, it would also reduce the chances of missing low-flying birds and would minimize the effects of receiver and MTI adjustments on the apparent density. Unfortunately, on medium powered radars similar to the ASR-5, ASR-7 or even the AASR-1, high-flying birds might be missed at $\frac{1}{4}$x or (1/3)x. On such radars it would appear to be impossible to avoid simultaneously the effects of changes in the height and speed distributions on the apparent migration density. On high-powered radars there should be little difficulty in detecting high-flying birds at (1/3)x, since x is 20 or more n.mi. (Nisbet, 1963:437). Hence on these radars it should be possible to minimize the effects of changes in both speed and height distributions.

Adjustable blind speeds are a feature of some MTI systems. One form of such circuitry, sometimes called Variable Velocity (VV) MTI, produces blind speeds that equal the usual ones (see above) plus or minus some constant. I have made occasional observations of the VVMTI video produced by one radar. As would be expected from theoretical considerations, the extent of bird suppression was comparable to that with normal MTI, but the 'MTI wedges' were no longer perpendicular to the axis of bird movement.

Another form of MTI incorporating adjustable blind speeds is the 'area cancellation' system described by Eastwood (1967:58-59). Here the blind speeds vary with azimuth, and can be adjusted such that on each azimuth the radial speed of a uniformly moving mass of clutter equals a blind speed. Eastwood describes the use of such circuitry to cancel rain echoes, thereby permitting birds to be seen in the presence of rain when the difference in radial speed between birds and rain is sufficiently great. I have no experience with this form of MTI. However, it is clear that it could be used to suppress bird echoes. With 'optimal' adjustment of the MTI, this suppression would be much more severe than that produced by a radar with fixed blind speeds or VVMTI. Suppression would be most severe if there were little variance in the directions and speeds of the bird targets. Bird suppression would be more severe with a double than with a single cancellation system. For maximum cancellation the system would be adjusted to the average speed and direction of the birds. Thus birds with speeds and directions differing greatly from the average would be more likely to remain visible than more typical targets. Hence such an MTI would be expected not only to suppress many birds but also to affect the direction and speed distributions of the birds which remained visible.

Surveillance radar installations are frequently arranged such that MTI-processed signals are displayed only at the centre of the PPI. Beyond some range (referred to as a range gate) normal video (ie., no MTI processing) is displayed. On some radars the position of the range gate is adjustable on each PPI; on others it is determined by a video mixer ahead of the line driver amplifier and hence cannot be adjusted separately on different PPI displays. The former arrangement is more versatile and hence preferable.

If the MTI is reducing the detectable range of some or all of the birds, and if the range gate is between the maximum detectable ranges with and without MTI, then more birds will be visible at ranges beyond the gate. Richardson (1970) and Richardson and Gunn (1971) show especially striking examples of this phenomenon When using radars on which MTI (alone or in combination with STC, circular polarization or the dynamic range problem discussed below) makes it impossible to see birds near the centre of the display, it may be possible to estimate the migration density in the normal video area beyond the range gate.

Birds flying over an area from which strong ground echoes are being received are less likely to be detected than the same birds flying over an area with no ground echoes, even though the ground clutter may be completely suppressed by the MTI. This occurs because the range of signal amplitudes which an MTI canceller can process (ie., the dynamic range of the MTI) is not as wide as the range of echo amplitudes that a radar may receive (Barton, 1964:196). When strong ground clutter is present in the same area as a moving target, the amplitude of the signal in that pulse volume contains a large clutter component, a small target component, and a still smaller receiver noise component. If the total of these three components is beyond the dynamic range, the total signal from that pulse volume must be limited before it reaches the canceller. The limiter reduces each of the three components by the same multiplicative factor. Thus if the total signal is limited by x db, the desired target will also be reduced x db. The strength of the target echo will be reduced further in the MTI canceller (say by y db) if its speed is not optimal. If (x+y) is greater than the amount by which the echo from the moving target originally exceeded the minimum detectable signal, the target will not be detected even though the ground clutter may be completely cancelled. Since bird targets are small, their S/N ratios are often also small, and hence even small amounts of limiting made necessary by strong ground clutter returns might make birds undetectable.

We have observed this phenomenon on many radars in Canada (eg., Richardson and Gunn, 1971:37). In areas of the displays in which dense clutter appears when using normal video, few birds are visible after cancellation of the clutter by MTI circuitry. In other areas of the same displays where the clutter is less dense or totally absent, birds are readily detected (Fig. 5A and B). A multivariate analysis of data obtained on 18 nights with the Halifax ASR-5 using 'normal' settings has confirmed this. After allowing for azimuthal thinning resulting from MTI cancellation, for radial thinning (sensu Nisbet, 1963), and for night to night variations in overall density, over 85% of the remaining variation in the numbers of targets detected in various sectors of the display was explainable on the basis of variations in the proportions of those sectors having ground clutter ($P << .001$ for the hypothesis that the number of birds detected in a given sector is not related to the proportion of that sector from which ground clutter is being received and cancelled)*.

* [illegible]

* The analysis was performed by computing the partial regression coefficients for the number of birds detected in areas with some clutter and in areas with no clutter after correcting for random overlap and after standardizing the total number of detected targets to 1000. A total of 15 pairs of coefficients were computed--one pair for each combination of the three range categories (1-3, 3-5, 5-7 n.mi.) and five azimuth categories (0-11, 12-33, 34-56, 57-78, 79-90 from the axis of the mean direction). All 15 multiple regression coefficients were significant ($P < .01$); 14 of the 15 had $P < .001$. Since the data used in the 15 regressions were independent, the probabilitie could be combined (Sokal and Rohlf, 1969:621) to give the overall $P \ll .001$ significanc level.

Suppression of echoes from birds because of limitations in the dynamic range of MTI circuits is not confined to Canadian radars: (i) Drury and Nisbet (1964:71) mention and illustrate but do not discuss the phenomenon. Drury et al. (1961:10) provide a striking example of suppression of bird echoes over land areas. Such a display is likely to occur when anomalous propagation conditions prevail (Nisbet, pers. comm.). AP produces ground echoes out to unusually long range over land but rarely over water. The MTI cancels the ground echoes, and also many of the birds flying in the same areas. (ii) The airport radar at Kloten, Switzerland detects few birds in certain specific areas (see radar photos in Sutter, 1957a,b; Gehring, 1963; and Steidinger, 1968). These areas are higher than the surrounding terrain (Sutter, 1957a:Fig. 3; Gehring, 1963:Fig. 1). Strong ground echoes are received from these areas (Sutter, 1957a,b). This can be seen in Sutter (1957a:Fig. 2, 10-12, 19-20), Sutter (1957b:Fig. 4F), and Steidinger (1968:Fig. 9c, 13, 15), in each of which the MTI was apparently not adjusted properly. When the areas of strong ground clutter were cancelled by the MTI, bird echoes in the same areas were suppressed as well. Suppression of birds in these areas was not simply the result of 'shadowing' (see above), since many birds were visible at greater ranges on the same azimuths.

It is clear that estimates of the density of migration made with radars having MTI circuitry must either be made in areas from which ground clutter is not received or else must be corrected for the losses of bird targets caused by signal limiting. On the basis of my analyses, it would appear that such correction could be quite accurate if ground clutter were not present over the whole area of interest.

Noncoherent Moving Target Indicator.--The above discussion dealt with coherent MTI, in which characteristics within the radar determine the radial velocities to be cancelled. All references to MTI in the ornithological literature to date deal with coherent MTI. In contrast, the radial speeds suppressed by several other forms of MTI, collectively referred to as noncoherent MTI, depend on the radial speeds of the echoes being received. The radial speeds found commonly in a given area of the display are suppressed, while point targets present in the same areas are not suppressed if they possess radial speeds different from those of the nearby clutter. Two forms of noncoherent MTI are the envelope-processing and clutter-locking systems described by Nathanson (1969).

Theoretically, one would expect noncoherent MTI systems to have effects similar to those of 'area cancellation' coherent MTI adjusted for maximum suppression. Cancellation should be much more severe than with a coherent MTI having fixed blind speeds. Birds with unusual speeds or directions are more likely to be detected than birds flying at or near the average speed and direction. Also, since noncoherent MTI cannot be used in the absence of clutter (Barton, 1964:223; Nathanson, 1969:323), one would expect noncoherent MTI systems to be switched on and off. Thus drastic temporal variations in detectability of birds are to be expected.

My experience with noncoherent MTI systems is limited. Noncoherent MTI is found on only a small proportion of the radars that I have used. However my observations show clearly that this circuitry does indeed suppress dense movements of passerines very severely. Thus when radars with such circuitry are used for bird surveillance it is essential to abstract the bird data from the radar before the signals are processed by the noncoherent MTI, or else to discard data collected when the circuitry was in use.

Channel changes

Most surveillance radars consist of two separate transmitter-receiver systems that may be operated alternately through the same antenna. Maintenance may be performed on one channel while the other is operating, thereby providing almost continuous operation. The two channels of each Canadian Air Traffic Control radar are supposed to be used for approximately equal numbers of hours and are to be alternated daily (Anon.,1964a: 1, 1969:19). Unfortunately, there can be differences between the two channels in almost all of the transmitter and receiver properties discussed above. Even on the infrequent occasions when the radar technicians try, they can rarely get identical displays from the two channels.

Even though the channels do vary in sensitivity, the apparent bird density rarely changes by as much as one unit on the 0-8 scale when the channels are switched. However, during part of the 1969 fall migration season one channel of the AASR-1 at Halifax was drastically inferior to the other; this was apparently a result of a combination of lower power output, higher minimum detectable signal, and poor tuning. The difference in apparent density between the channels in this extreme case is shown in Fig. 5C and D. It was possible to establish the relationship between the apparent densities on the two AASR-1 channels by comparing apparent densities before and/after channel changes and by cross-checking with the ASR-5 which was operating simultaneously at the same site. By knowing which channel was in use, it was then possible to make reasonably consistent estimates of migration density even though the channels produced very different apparent densities.

Display adjustments

The above sections refer to variations in the apparent density of migration caused by changes in settings or performance of the radar itself, or by interactions between the type of bird movement and the capabilities of the radar. Adjustments of the display on which the radar data are presented can also affect the apparent density. The display gain and trace brilliance should ideally be set initially at optimal values and then not changed. Unfortunately, instabilities in the display occasionally necessitate adjustments to the display gain and trace brilliance. One must therefore adopt some standards and readjust the display to them as necessary. For example, the trace brilliance is usually set so that the trace is barely visible in a darkened room when the video is switched off. Fortunately, slight variations in gain and trace brilliance change the apparent density by only a small fraction of a unit of the 0-8 scale.

The resolution of the total system may be limited not only by the resolution of the beam (see pulse-volume section above), but also by the spot-size on the display (Eastwood, 1967:83). If the display cannot produce a spot smaller than the horizontal dimensions of the pulse-volume on the scale of the display, the spot size will be the limiting factor. This is most likely to occur on a radar producing short pulses (eg., the

ASR-5 or ASR-7) or when the display is set to show a large area. Accurate focussing of the display is obviously required for maximum resolution. High resolution is very desirable both for counting targets and for determining their directions of movement. Some of our radars occasionally detect flocks at a range of 100 n.mi. or more. However, in order to maximize resolution of the passerine targets at closer range, we rarely display an area of radius more than 70 n.mi..

Digitized radar data

In the SAGE/BUIC system of the North American Air Defense Command (NORAD), the original analogue radar data are converted to digital form by a computer at each site and then transmitted to various Control Centres. Corddry (1963) gives a general description of the system. One of the purposes of digitization is to provide further means for suppressing undesired echoes from the ground, weather and birds. The criteria used by the computer in deciding whether or not to suppress the return from a given pulse volume are classified. However, they can be changed from hour to hour, thereby modifying the proportion of the birds which is suppressed.

I have observed various digitized displays several times per day over periods totalling 16 weeks. I was able to compare two of the digitized displays with the original analogue PPI displays from which they were derived. The digitiz displays usually showed many fewer bird echoes than the corresponding analogue displays. Weak echoes from passerines were completely suppressed most of the time However on most occasions at most radar sites at least some intense echoes, presumably from flocks, were still visible on the digitized PPI displays. In fact these larger targets were frequently easier to track on the digitized displays sinc these showed less clutter (ground, weather, passerines) than the original analogue displays. Thus, while NORAD digitized displays do not provide useful information about the amount of migration, they can usually provide information about the flight directions of flocks of birds.

During the day the digitized data are less biased than during the night. By day I have rarely found any difference in the direction distributions of the bird echoes visible on the analogue and digitized displays. At night there often is such a difference. There are two probable reasons for the more frequent directional bias at night: (i) By day the average migration density is much less than it is at night (Richardson, 1970 and unpubl.). Hence by day less stringent suppression criteria in both the radar and the digitizer are generally sufficient to reduce the 'bird clutter' to an acceptable level. (ii) By day most birds migrate in flocks producing strong echoes (Gehring, 1963; Steidinger, 1968:199; Bruderer, 1969:76; Gauthreaux, 1970,1971; Richardson and Gunn, 1971 and unpubl.). By night a wider range of echo strengths occurs, and the weak echoes are suppressed during digitization. The weak echoes often have a different mean direction than the stronger echoes present simultaneously. Thus when the weak echoes are suppressed, the apparent overall mean direction changes*.

At a NORAD Control Centre one can observe the digitized data from many radar sites simultaneously. Thus one can easily study the progressive changes in the distributions of flight directions of flocks of birds at various sites as pressure systems and fronts move across a wide area. Richardson (1971,1972) shows such series of observations. The data are biased in favour of large flocks, but for some purposes (bird hazard to aircraft studies; waterfowl surveys) this may not be a serious disadvantage.

---

* Similar changes in the apparent distribution of flight directions are often produced by radar adjustments that suppress weak passerine echoes. For example, when STC, circular polarization, or CFAR are switched on, the weakest echoes may be suppressed while the stronger ones are still detected. If the weak echoes have a different direction distribution than the stronger ones, a change in the apparent direction distribution will result.

In the United States, the original analogue displays from various FAA long-range radars have been transmitted to single Air Route Traffic Control Centres (Anon., 1964b). Hence the suppression of many bird targets that occurs during digitization has not been a problem in studies of migration at FAA Control Centres (Flock and Bellrsoe, 1970). However, the FAA is at present converting to a nationwide digitized radar system (Anon., 1971; Cornell, 1971). Hence the quality of the migration data available at the FAA Control Centres will probably soon be reduced to a level similar to that of the bird information now available at the NORAD centres.

IMPLICATIONS AND CONCLUSIONS

1. When studying migration with a long range surveillance radar that is simultaneously being used for other purposes, one can expect frequent adjustments of the radar. The adjustments which seem to have the largest effect on the apparent density of migration are

   (i) Use of STC, especially on low-powered radars where the density must be estimated within a few miles of the site.

   (ii) Circular polarization, which produces a consistent reduction in the apparent density on almost all radars.

   (iii) FTC, IAGC and CFAR, which produce important reductions only when the migration density is high. These circuits are rarely used on many radars.

   (iv) Complex combinations of adjustments to the various receivers used on stacked-beam radars. If at all possible, it is preferable to use 'raw video' even though ground clutter becomes a problem.

   (v) Infrequent changes in IF gain can produce effects varying from nil to severe.

(vi) MTI produces complex effects on the display of birds. The severity of MTI suppression depends on the type and adjustment of the MTI circuitry, other characteristics of the radar, the size, speed, azimuth, flight direction and range of the bird targets, and the extensiveness of the cancelled ground clutter. The extensiveness of the cancelled clutter present at a given site and time is, in turn, dependent on atmospheric conditions.

Some adjustments (tuning errors, channel changes) usually have little effect, but occasionally may produce severely reduced apparent densities.

2. Adjustments in radar performance usually have their greatest effect on echoes at long range and on fine passerine-type echoes, no doubt because such echoes are close to the threshold of detection.

3. Compounding of the effects discussed in this paper may occur. While the effects of individual changes in radar settings are frequently consistent and not very severe, they are additive. For example, MTI suppression of a target not moving at the optimal speed and suppression by circular polarization may not individually be severe enough to prevent that target from being detected. However, acting together they may reduce the S/N ratio so that it is below the detection threshold.

4. If reliable quantitative information about migration is to be obtained from a surveillance radar, one must know the behaviour and mode of operation of that individual radar. Different individual radars, even those of the same model, often behave differently.

5. If one knows the radar settings in use at any given time and if one has studied the effect of each departure from the 'normal' settings on the apparent density, then it will usually be possible to make appropriate corrections of

the apparent density in order to estimate the density which would have appeared if 'normal' settings had been used. If there is only one departure from the normal settings, it should be possible to estimate the actual density of migration within one unit on my 0-8 scale. If there are several simultaneous departures from 'normal' settings, the accuracy of the corrected estimate is not likely to be as great. Even certain single adjustments (such as use of STC on a low-powered radar) may have such a strong effect on the apparent density that accurate correction is impossible. In many analyses it is preferable to discard such questionable information and to work with a smaller pool of more accurate data.

6. The detectability of birds at a given range can vary with azimuth. Aspect, MTI wedge shadowing effects and the dynamic range of MTI systems are the causes. Hence one must give consideration to which part of the display is to be used for estimating densities.

7. When using a radar with a csc^2 beam pattern (typical of search radars), density estimates must be made between 5 and 30 n.mi. to avoid biases based on height of flight. When using MTI, density estimates must be made at less than ½ the normal video detection range of the smallest bird targets in order to avoid biases based on ground speeds.

8. When using a radar like the ASR-5 which does not detect individual passerines at ranges beyond 4 or 5 n.mi., it is likely to be impossible to select an area of the display which is simultaneously close enough to avoid suppression of small slow targets and far enough away to detect birds at high altitude. Thus at least one of these types of bias is inevitable in data from such radars.

9. During even moderately intense migration, the display is saturated with bird echoes at the ranges required by (7). In such cases, the range to which saturation occurs is an indicator of density. However, that range is also strongly affected by the height, ground speed and RCS distributions of the birds and by anomalous propagation, shadows behind hills, and adjustments of the radar. Thus, in accordance

with Lack (1962) and Nisbet (1963), I conclude that it is not possible to estimate accurately the density of intense migrations. However, dense movements can readily be identified as such. Only nocturnal passerine movements are dense enough to produce saturation on a regular basis. In some areas (such as Nova Scotia), even these movements are rarely dense enough to produce complete saturation near the centre of an expanded display.

10. The adjustments of an air surveillance radar can often be changed briefly without disturbing normal operations. Thus it is often possible to obtain a reliable density estimate by switching from non-optimal to optimal settings for a minute or less.

11. The reliability of density estimates can be enhanced considerably by simultaneous use of more than one radar at a single site. A combination of a high-powered surveillance radar and a height-finder is particularly versatile for studies of migration.

12. In general, one should recognize that surveillance radars are not carefully calibrated precision instruments. While these radars can provide excellent qualitative information about migration, even with careful use they can provide only moderately accurate quantitative data. Fortunately, temporal variations in the amount of migration and in migratory behavior are so marked that the data which such radars can provide are sufficiently accurate for many types of analysis.

ACKNOWLEDGMENTS

I thank the Telecommunications Maintenance and Air Traffic Control personnel at Halifax and Moncton Airports and the maintenance and operations personnel at Canadian Forces Stations Barrington, St Margarets and Sydney for their assistance, advice and tolerance during these and other studies. I am grateful to the U.S. National Aeronautics and Space Administration, Wallops Station, Virginia for giving me access to the ASR-7, and to W.D. Beishline for help in making the ASR-7 tests.

I thank Capt. G.L. Shufflebotham and Lt. J.E. Anderson (21 Radar Sqn., St Margarets, N.B.), F.R. Hunt (Radio and Electrical Engineering Division, NRC), H. Blokpoel, S.T. Emlen, W.W.H. Gunn, I.C.T. Nisbet, C.J. Ralph, D.K. Riker and T.C. Williams, who read the manuscript and provided valuable comments and criticisms.

This study was financed by the National Research Council of Canada through its Associate Committee on Bird Hazards to Aircraft.

LITERATURE CITED

ABLE, K.P. 1970a. Nocturnal bird migrants: two methods of flight orientation? Bull. Ecol. Soc. Amer. 51:43.

-------- 1970b. A radar study of the altitude of nocturnal passerine migration. Bird-Banding 41:282-290.

ADAMS, D.W.H. 1962. Radar observations of bird migration in Cyprus. Ibis, 104:133-146.

Anonymous. 1956. Radar network for traffic control in Canada. Interavia 11:545

--------. 1964a. Radar equipment maintenance standards C5-1. Airport and Airways Surveillance Radar and Associated Equipment. Dept. of Transport, Air Services. Ottawa, Canada.

--------. 1964b. Air traffic control in the USA. Interavia 19:1525-1530; 1808-1811.

--------. 1965. US radar catalogue. Interavia 20:59-62

--------. 1969. Radar equipment maintenance standards C5-6. ASR-5 Radar. Dept. of Transport, Air Services. Ottawa, Canada.

--------. 1971. Implementing the FAA 10 year plan. Interavia 26:937-938.

AXELL, H.E., D. LACK, J.L.F. PARSLOW and J. WILCOCK. 1963. Migration at Minsmere, seen and unseen. Bird Notes, 30:181-186.

BARTON, D.K. 1964. Radar system analysis. Englewood Cliffs, N.J.:Prentice-Hall, Inc.

BELLROSE, F.C. 1964. Radar studies of waterfowl migration. Trans. 29th N. Amer. Wildl. and Nat. Resources Conf.:128-143.

--------. 1967. Radar in orientation research. Proc. XIV Intern. Ornith. Cong.: 281-309.

--------. 1968. Waterfowl migration corridors east of the Rocky Mountains in the United States. Illinois Natural History Survey, Biol. Notes No. 61.

BLOKPOEL, H. 1970a. An attempt to forecast the intensity of nocturnal fall bird migration. Proc. World Conf. Bird Hazards to Aircraft:285-298.

--------. 1970b. A preliminary study on height and density of nocturnal fall migration. Proc. World Conf. Bird Hazards to Aircraft:335-348. Reprinted in Canad. Wildl. Serv. Report Ser. 14:95-104.

--------. 1970c. A further attempt to forecast bird migration over Cold Lake, Alberta. Associate Comm. on Bird Hazards to Aircraft, Field Note 54.

-------. 1971. The M33C track radar (3-cm) as a tool to study height and density of bird migration. Canad. Wildl. Serv. Report Ser. 14:77-94.

------- and P.P. DESFOSSES. 1970. Radar observations of local bird movement near Calgary, Alberta. Assoc. Comm. on Bird Hazards to Aircraft, Field Note 53.

BRUDERER, B. 1969. Zur Registrierung und Interpretation von Echosignaturen an einem 3-cm-Zielverfolgungsradar. Ornithol. Beob. 66:70-88.

-------. 1971. Radarbeobachtungen über den Frühlingszug im Schweizerischen Mittelland. Ornithol. Beob. 68:89-158.

------ and J. JOSS. 1969. Methoden und Probleme der Bestimmung von Radarquerschnitten frei fliegender Vögel. Rev. Suisse de Zool. 76:1106-1118.

CORDDRY, C. 1957. The U.S. and Canadian radar warning chains. Interavia, 12:566-568

-------. 1963. North America's electronic shield against air attack. Interavia, 18:582-589.

CORNELL, D. 1971. ATC planning in the USA. Interavia, 26:135.

DRURY, W.H. Jr. and I.C.T. NISBET. 1964. Radar studies of orientation of songbird migrants in coastal New England. Bird-Banding 35:69-119.

-------,------- and R.E. RICHARDSON. 1961. The migration of "angels". Natural History, 70(8):10-17.

EASTWOOD, E. 1967. Radar ornithology. London: Methuen & Co. Ltd.

EDWARDS, J. and E.W. HOUGHTON. 1959. Radar echoing area polar diagrams of birds. Nature, 184:1059.

EVANS, P.R. 1966. An approach to the analysis of visible migration and a comparison with radar observations. Ardea, 54:14-44.

FERRY, V.E.F. 1970. De l'utilisation operationnelle des renseignements fournis par le radar. Proc. World Conf. Bird Hazards to Aircraft:269-272.

FLOCK, W.L. 1968. Monitoring bird movements by radar. IEEE Spectrum, 5:62-66.

-------- and F. BELLROSE. 1970. A radar study of bird migration in the central United States. Proc. World Conf. Bird Hazards to Aircraft:273-283

GAUTHREAUX, S.A. Jr. 1970. Weather radar quantification of bird migration. Bio Science, 20:17-20

------- 1971. A radar and direct visual study of passerine spring migration in southern Louisiana. Auk, 88:343-365.

------- and ABLE, K.P. 1970. Wind and the direction of nocturnal songbird migration. Nature, 228:476-477.

GEHRING, W. 1963. Radar- und Feldbeobachtungen über den Verlauf des Vogelzuges im Schweizerischen Mittelland: Der Tagzug im Herbst (1957-1961). Ornithol. Beob. 60:35-68.

--------. 1967. Radarbeobachtungen über den Vogelzug am Col de Bretolet in den Walliser Alpen. Ornithol. Beob. 64:133-145.

GUNN, W.W.H. 1964. Radar photography study of bird migration. Preliminary report on methods, 1963-4. Assoc. Committee Bird Hazards to Aircraft, Field Note No. 19.

-------- and SOLMAN, V.E.F. 1968. A bird warning system for aircraft in flight. pp 87-96 in Murton, R.k. and E.N. Wright (ed.) The Problems of birds as pests. Institute of Biology Symposia No. 17. New York: Academic Press.

HARPER, W.G. 1957. 'Angels' on centimetric radars caused by birds. Nature, 180:847-849.

--------. 1958. Detection of bird migration by centimetric radar--a cause of radar 'angels'. Proc. Royal Soc. B,149-484-502.

HILD, J. 1969. Meteorologische Aspekte zum Problem Vogelschlag im Luftverkehr. Wetter und Leben,21:1-11

--------. 1970. Bird movement forecast in Germany. Proc. World Conf. Bird Hazards to Aircraft:349-357.

HOUGHTON, E.W. 1964. Detection, recognition and identification of birds on radar. Proc. World Conf. on Radio Meteorology, incorporating 11th Weather Radar Conf.:14-21.

--------, 1969. Radar echoing areas of birds. RRE Memorandum,2557:1-13.

JACKSON, W.B. And L.K. FIEDLER. 1970. Radar studies of crow flocks at the Toledo airport. Proc. World Conf. Bird Hazards to Aircraft:253-264.

KEIL, W. 1970. The crane migration in Germany in connection with weather and radar. Proc. World Conf. Bird Hazards to Aircraft:245-251.

KONRAD, T.G., J.J. HICKS, and E.B. DOBSON. 1967. Radar characteristics of birds in flight. Science,159:274-280.

KUHRING, M.S. and W.W.H. GUNN. 1965. Birds/Radar/Weather. Assoc. Committee on Bird Hazards to Aircraft, Field Note No. 29.

LACK, D. 1959. Migration across the North Sea studied by radar. Part 1. Survey through the year. Ibis, 101:209-234.

-------. 1962. Migration across the southern North Sea studied by radar. Part 3. Movements in June and July. Ibis, 104:74-85.

-------. 1963. Migration across the southern North Sea studied by radar. Part 4. Autumn. Ibis, 105:1-54.

LEE, S.L.B. 1963. Migration in the outer Hebrides studied by radar. Ibis, 105: 493-515.

MASCHER, J.W., B.-O. STOLT, and L. WALLIN. 1962. Migration in spring recorded by radar and field observations in Sweden. Ibis, 104:205-215.

MEINERTZHAGEN, R. 1955. The speed and altitude of bird flight (with notes on other animals). Ibis, 97:81-117.

MULHOLLAND, E.B. and F.R. SODEN. 1967. Australia's ATC radar network. Interavia, 22:511-513.

MYRES, M.T. 1963. Observations with radar of the feeding flights of Kittiwakes. Bird Study, 10:34-43.

-------. 1964a. Technical details of radar equipment detecting birds, and a bibliography of papers reporting the observation of birds with radar. Assoc. Committee on Bird Hazards to Aircraft, Field Note No. 9.

--------. 1964b. Dawn ascent and reorientation of Scandinavian thrushes (Turdus spp) migrating at night over the northeastern Atlantic Ocean in autumn. Ibis 106:7-51.

---------. 1969. Uses of radar in wildlife management. pp 105-108 in Giles, R.H. Jr. (ed.) Wildlife Management Techniques. Washington, D.C.:The Wildlife Society.

---------. 1970. The detection of birds and insects, and the study of bird movements, with radar. (A résumé with bibliography). Proc. World Conf. Bird Hazards to Aircraft:501-519.

------- and CANNINGS, S.R. 1971. A Canada Goose migration through the southern interior of British Columbia. Canad. Wildl. Serv. Report Ser. 14:23-34.

NATHANSON, F.E. 1969. Radar design principles. New York:McGraw Hill.

NISBET, I.C.T. 1963. Quantitative study of migration with 23-centimeter radar. Ibis, 105:435-460.

-------, W.H. DRURY, Jr., and J. BAIRD. 1963. Weight-loss during migration. Part I: Deposition and consumption of fat by the Blackpoll Warbler Dendroica striata. Bird-Banding, 34:107-138.

PARSLOW, J.L.F. 1969. The migration of passerine night migrants across the English Channel studied by radar. Ibis, 111:43-79.

RAVERDY, J. 1962. The use of circular polarisation in radar. Interavia, 17:892-893.

RINEHART, R.E. 1966. Radar detection of birds in New Mexico. Proc. 12th Conf. on Radar Meteorology:1-6.

RICHARDSON, W.J. 1970. Temporal variations in the volume of bird migration: a radar study in Canada. Proc. World Conf. Bird Hazards to Aircraft:323-334.

-------. 1971. Spring migration and weather in eastern Canada: A radar study. Amer. Birds, 25:684-690.

-------. 1972. Autumn migration and weather in eastern Canada: A radar study. Amer. Birds, 26: (in press).

------- and W.W.H. GUNN. 1971. Radar observations of bird movements in east-central Alberta. Canad. Wildl. Serv. Report Ser. 14:35-68.

-------- and M.E. HAIGHT. 1970. Migration departures from Starling roosts. Canad. J. Zool. 48:31-39.

SCHAEFER, G.W. 1968. Bird recognition by radar. A study in quantitative radar ornithology. pp 53-56 in Murton, R.K. and E.N. Wright (ed.) The Problems of Birds as Pests. Institute of Biology Symposia No. 17. New York:Academic Press.

SCHNELL, G.D. 1965. Recording the flight speed of birds by Doppler radar. The Living Bird, 4:79-87.

SIEGEL, S. 1956. Nonparametric statistics for the behavioral sciences. New York: McGraw-Hill.

SOKAL, R.R. and F.J. ROHLF. 1969. Biometry. San Francisco: W.H. Freeman.

SPIERS, J.M., J.J.C. KANITZ, and J. NOVAK. 1971. Numbers, speeds, and directions of migrating geese from analysis of a radar display at Fort William, Ontario. Canad. Wildl. Serv. Report Ser. 14:69-76.

STEIDINGER, P. 1968. Radarbeobachtungen über die Richtung und deren Streuung beim nächtlichen Vogelzug im Schweizerischen Mittelland. Ornithol. Beob. 65: 197-226.

SUTTER, E. 1957a. Radar als Hilfsmittel der Vogelzugsforschung. Ornithol. Beob. 54:70-96.

-------. 1957b. Radar-Beobachtungen über den Verlauf des nächtlichen Vogelzuges. Rev. Suisse Zool. 64:294-303.

TEDD, J.G. and D. LACK. 1958. The detection of bird migration by high-power radar. Proc. Royal Soc. B, 149:503-510.

TUCKER, V.A. and K. SCHMIDT-KOENIG. 1971. Flight speeds of birds in relation to energetics and wind direction. Auk, 88:97-107.

WARDEN, M.P. and B.A. WYNDHAM. 1970 Measurements of radar echoes from migrating birds. Proc. World Conf. Bird Hazards to Aircraft: 491-497.

WEISHAUPT, M.G. 1970. Surveillance radar des deplacements d'oiseaux en France. Stages de formation des controleurs radar. Proc. World Conf. Bird Hazards to Aircraft: 485-490.

WILCOCK, J. 1964. Radar and visible migration in Norfolk, England: a comparison. Ibis 106: 101-109.

-------. 1965. Detection by radar of autumn migration in eastern Scotland. Ibis, 107: 316-325.

FIGURE LEGENDS

Figure 1. Effect of ASR-5 radar adjustments on the number of bird targets detected. The number detected with a changed setting is plotted on the ordinate against the number with 'normal' settings (as defined in the Methods) plotted on the abscissa. The diagonal line is the expected position of the points if the changed setting had no effect. Circles, squares and triangles are counts in the range categories 1-3, 3-5, and 5-7 n.mi. respectively. Significance levels (*--$P<.05$; **--$P<.01$) are for one-tailed Wilcoxon matched-pairs signed ranks tests of the hypothesis that the change in setting had no effect. In these tests the counts in the three range categories at one time were treated as separate data points.

Figure 2. Birds visible with various ASR-5 radar settings (Halifax, Nova Scotia; 29 August 1969 at 0155-0200 AST). Each photo (except that labelled '2 min') shows one sweep of four seconds duration. Magnetic north (23° W of true N) is at the 12 o'clock position. The '2 minute' photo is a time exposure with normal settings in which the directions of the lines indicate the directions of bird movement (SSE-WSW at this time). No non-avian targets are visible. The bright circle demarks an area with 5 n.mi. radius.

Figure 3. Effect of AASR-1 radar adjustments on the number of bird targets detected. Plotted as in Fig. 1, except that the left and right figures of each pair show the numbers detected at 10-15 and 15-20 n.mi. respectively.

Figure 4. Birds visible with various AASR-1 radar settings (Moncton, New Brunswick; 17 May 1970 at 0007-0029 AST). Each photo is a three-minute time exposure (18 sweeps). Magnetic north (23° W of true N) is at the 12 o'clock position. Each bird target is shown as a short streak; other types of targets are ground clutter visible in spite of the MTI or superimposed bird 'streaks'. The bright circle near the edge of each photo demarks an area with 20 n.mi. radius.

Figure 5. Variations in detectability of birds. Sections A and B illustrate the effect of the limited dynamic range of the MTI on detection of birds. Few or no birds are detected (on B, a 2 min. time exposure) in areas from which intense ground clutter (visible on A with normal video at a time when no birds were detected) is being cancelled. C and D show the effect on a dense passerine movement of a change in channels on the Halifax AASR-1 during the period when channel B was drastically inferior to channel A (4 October 1969; 2316 AST). E and F show the effect on a dense passerine movement of a change from horizontal to circular polarization using the Halifax AASR-1 (channel A; 23 October 1969; 1942 AST). In C-F range marks are at 10 n.mi. intervals and all the echoes are from birds.

Figure 6. Intensity scale used to record the amount of migration visible with the Halifax AASR-1 radar. Intensity levels 1 (very light) to 8 (extremely heavy) are shown. The thick outermost range-ring indicates a radius of 50 nautical miles (93 km). Magnetic north (337° True) is in the 12 o'clock position.

Figure 7. Effect of changes in MTI mode on the number of birds detected (ASR-5 radar at Halifax, N.S.; 18 October 1969 at 2242 AST). 'Normal' is double cancellation MTI without feedback; '30, 35 and 40 db Sub-clutter visibility' are modes of MTI using double cancellation plus varying amounts of feedback. Fig. 8 shows the velocity response curve for these modes of MTI. Note the pronounced effect of changes in mode at long range (ie., beyond the circle with radius 5 n.mi.).

Figure 8. Theoretical effects of the modes of MTI available on ASR-5 radars on the amplitude of targets having various radial speeds. The 25, 30, 35 and 40 db SCV modes of MTI use two cancellers plus a variable amount of feedback.

Figure 9. Birds visible with various ASR-7 radar settings (Wallops Station, Virginia; 1 November 1971 at 1058-1103 EST). Each photo shows one sweep of 4.6 sec. duration. Double cancellation MTI with feedback ('35 db SCV' mode) was used in all cases except the single and double cancellation without feedback tests. Magnetic north (8° W of geographic north) is at the 12 o'clock position. An area of radius 10 n.mi. is shown.

TABLE 1. CHARACTERISTICS OF AASR-1 AND ASR-5 RADARS

	AASR-1	ASR-5
Manufacturer	Raytheon	Texas Instrument Co.
Wavelength	22.5 cm (L-band)	10.7 cm (S-band)
Peak power output	550 kW	400 kW
Pulse repetition ffequency (prf)	363/sec	1200/sec
PRF stagger ratio	Not staggered	0.818
First MTI blind speed		
-non-staggered operation	78 kts	126 kts
-staggered operation	------	1260 kts
Pulse duration	2.0 μsec	0.833 μsec
Minimum detectable signal		
-using MTI	-104 dbm or better*	-107 dbm or better*
-not using MTI	-106 dbm " "	-109 dbm " "
Receiver noise figure	8½ db or less*	4½ db or less*
Scanning rate	6 rpm	15 rpm
Beamwidths (½ power points)		
-horizontal	1.35^{o}	1.5^{o}**
-vertical	6.5^{o}***	6.5^{o}***
Antenna gain	34 db	34 db
Polarization	Horizontal or Circular	Vertical or Circular

* Normally 1 to 3 db better than these operating limits

** 3^{o} at 10% and 4^{o} at 2% power points

*** Approximately csc^2 pattern from upper half-power point to 30^{o} elevation

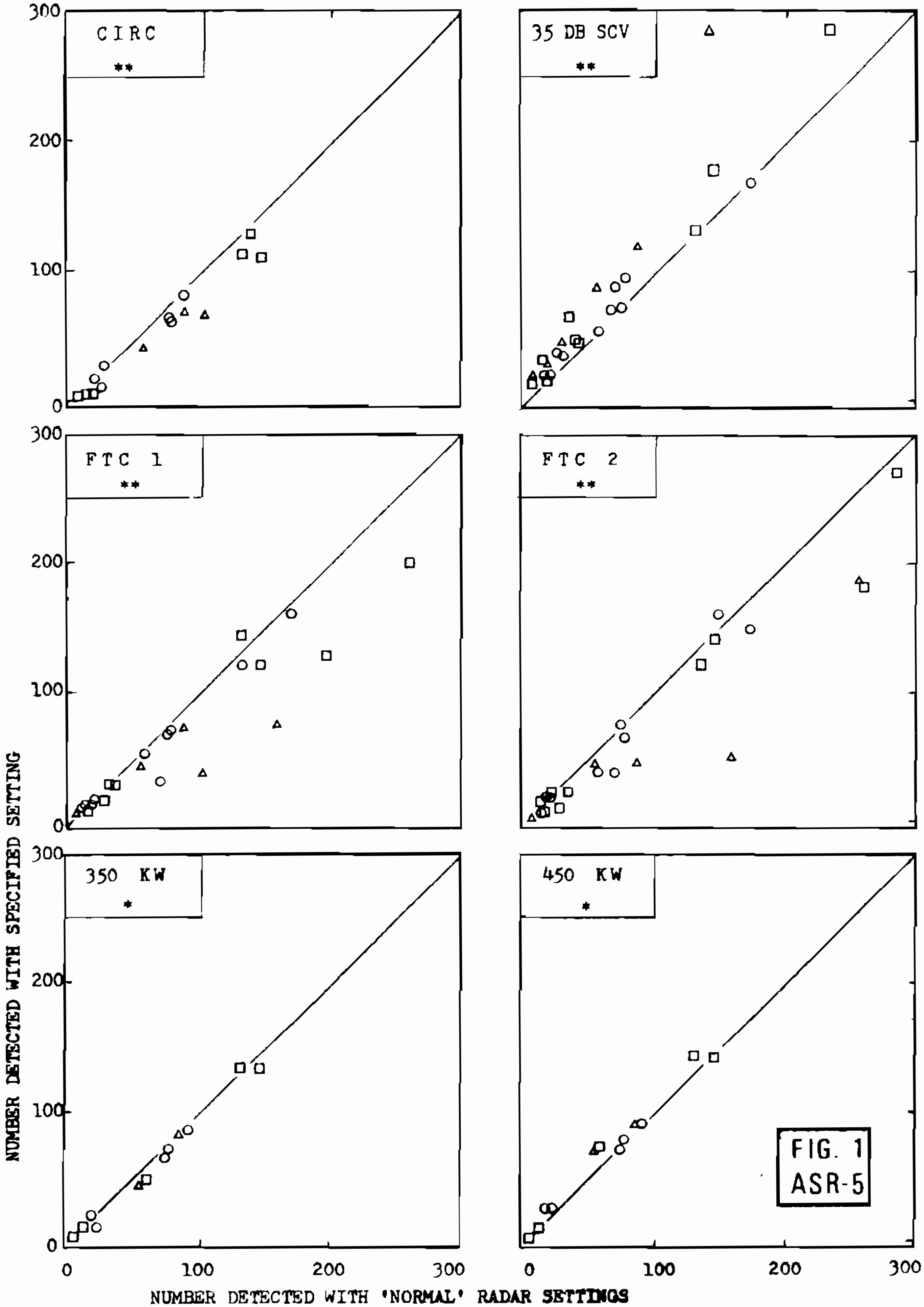
TABLE 2. CHANGE IN NUMBER OF BIRD ECHOES DETECTED WITH VARIOUS RADAR ADJUSTMENTS. SUMMED OVER ALL SERIES.†

Changed setting	Changed As % of Normal			Total N with changed settings.			Number of Series of Data	
ASR-5 TESTS Range (n.mi.)=	1-3	3-5	5-7	1-3	3-5	5-7		
Circular polarization	88.7	83.0	75.1	259	362	178	6*	
MTI mode 35 db SCV	110.3	130.7	187.3	640	910	633	10**	
FTC 1	92.1	81.4	58.9	569	669	234	9**	
FTC 2	89.4	87.1	59.6	567	837	331	9**	
350 kW peak power	89.8	94.4	93.4	247	323	128	5*	
450 kW peak power	104.0	107.0	116.1	286	159	366	5*	
AASR-1 TESTS Range (n.mi.)=	10-15	15-20		10-15	15-20		10-15	15-20
STC	59.7	100.0		417	427		12	16
FTC 1	85.4	87.4		596	373		12	16
FTC 2	85.8	93.7		599	400		12	16
Circular polarization	46.1	45.7		244	177		10	14

† Significance levels are given on Figures 1 and 3.

* On 3 of these nights no bird echoes were visible in the 5-7 n.mi. category with either normal or modified radar settings

** On 4 of these nights none visible at 5-7 n.mi..



CIRC
**
35 DB SCV
**
FTC 1
**
FTC 2
**
350 KW
*
450 KW
*
0
100
200
300
NUMBER DETECTED WITH SPECIFIED SETTING
NUMBER DETECTED WITH 'NORMAL' RADAR SETTINGS

FIG. 1
ASR-5

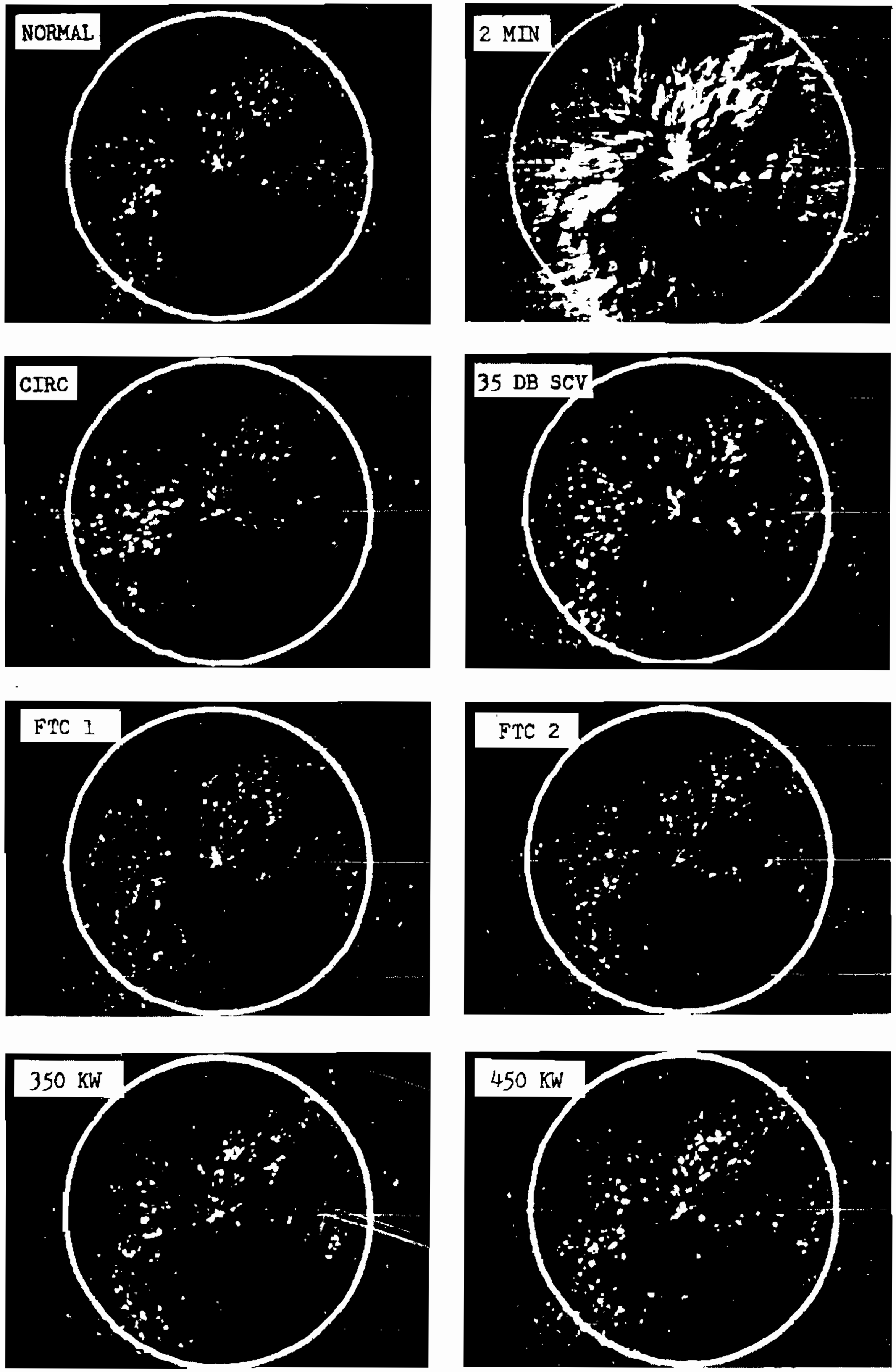


FIGURE 2. ASR-5 ADJUSTMENTS

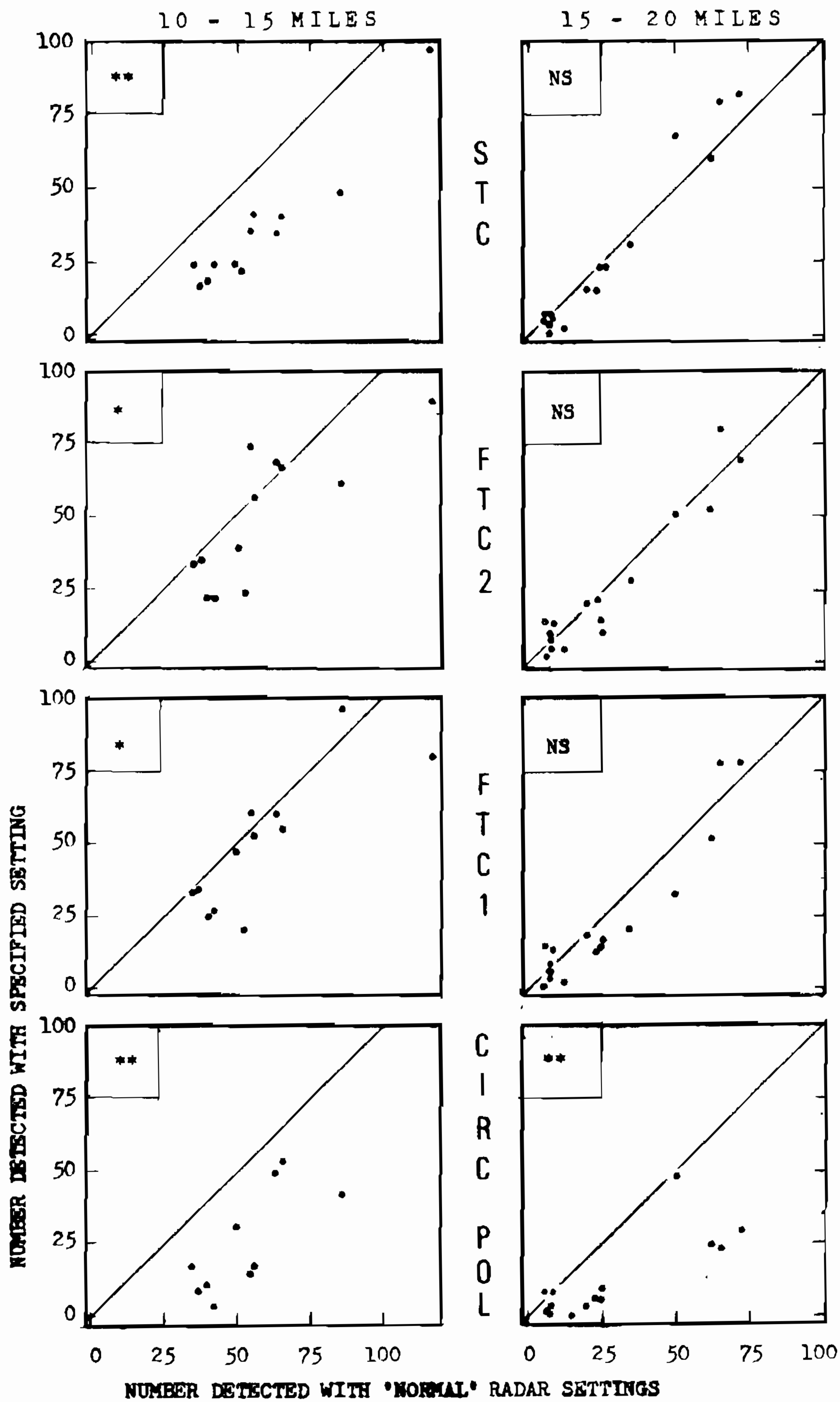

10 - 15 MILES
15 - 20 MILES
STC
FTC 2
FTC 1
CIRC POL
**
NS
*
NS
*
NS
**
**
100
75
50
25
0
0
25
50
75
100
NUMBER DETECTED WITH SPECIFIED SETTING
NUMBER DETECTED WITH 'NORMAL' RADAR SETTINGS

FIG. 3: AASR-1

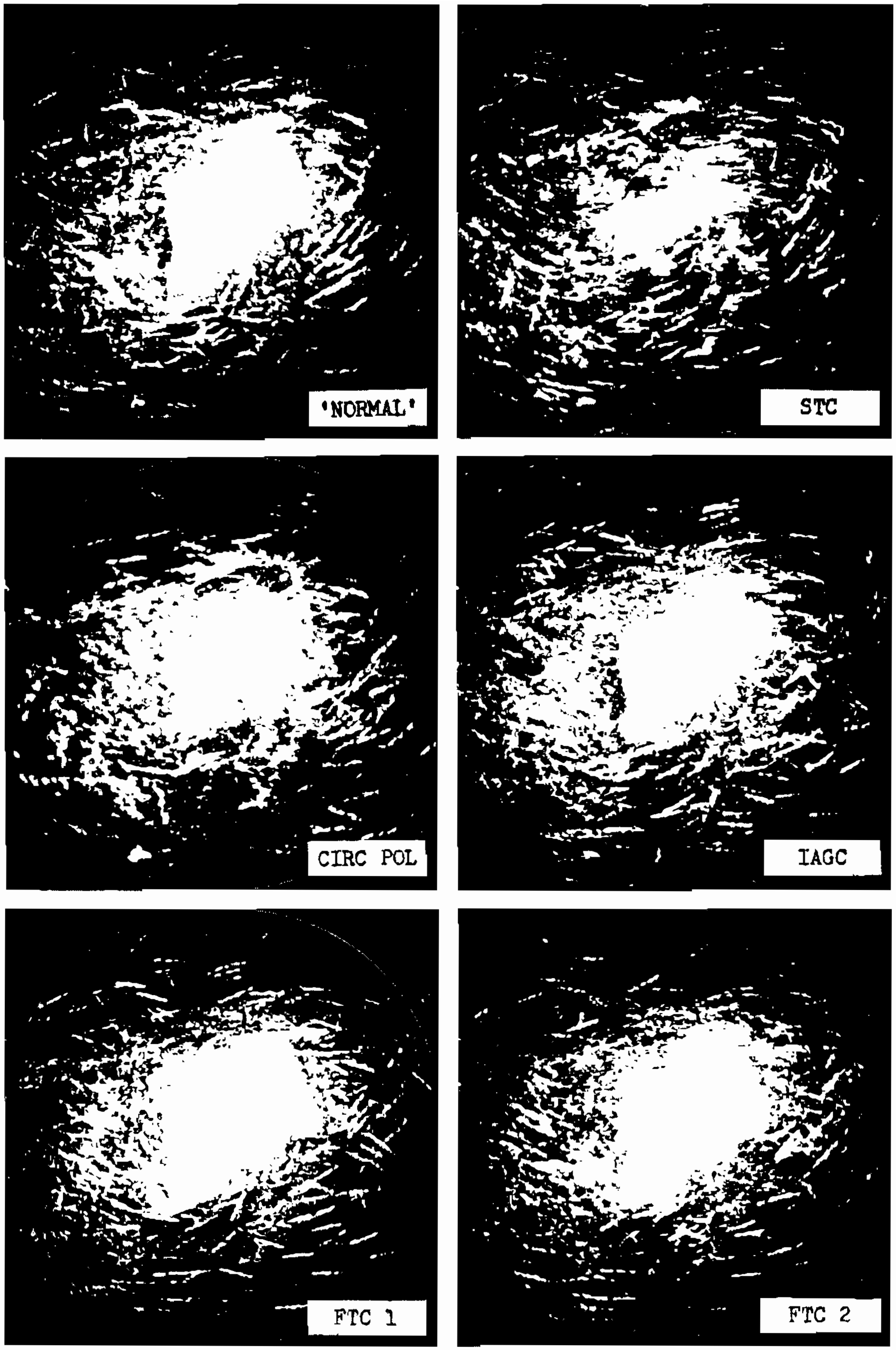


FIGURE 4. AASR-1 ADJUSTMENTS

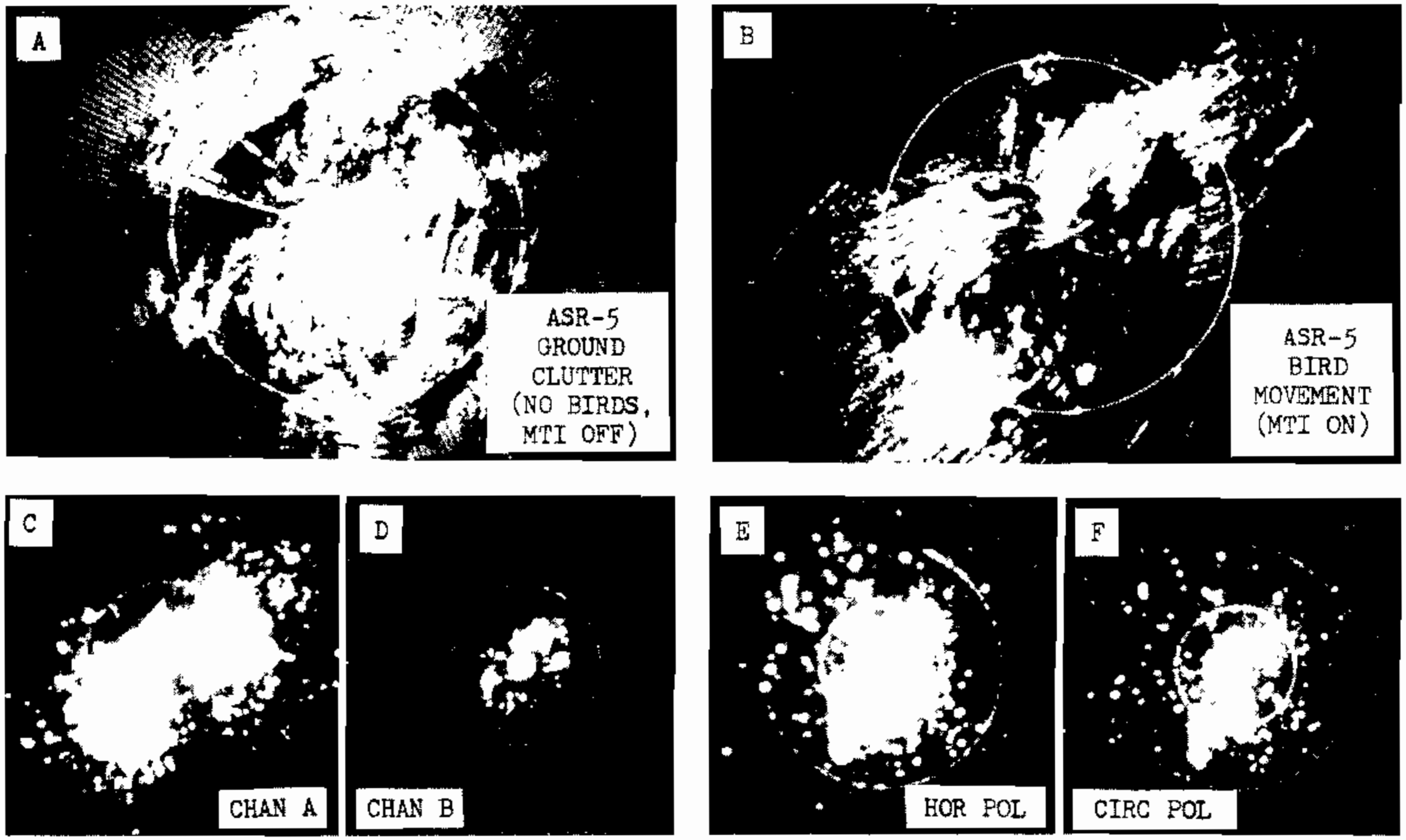


FIGURE 5. VARIATIONS IN SENSITIVITY

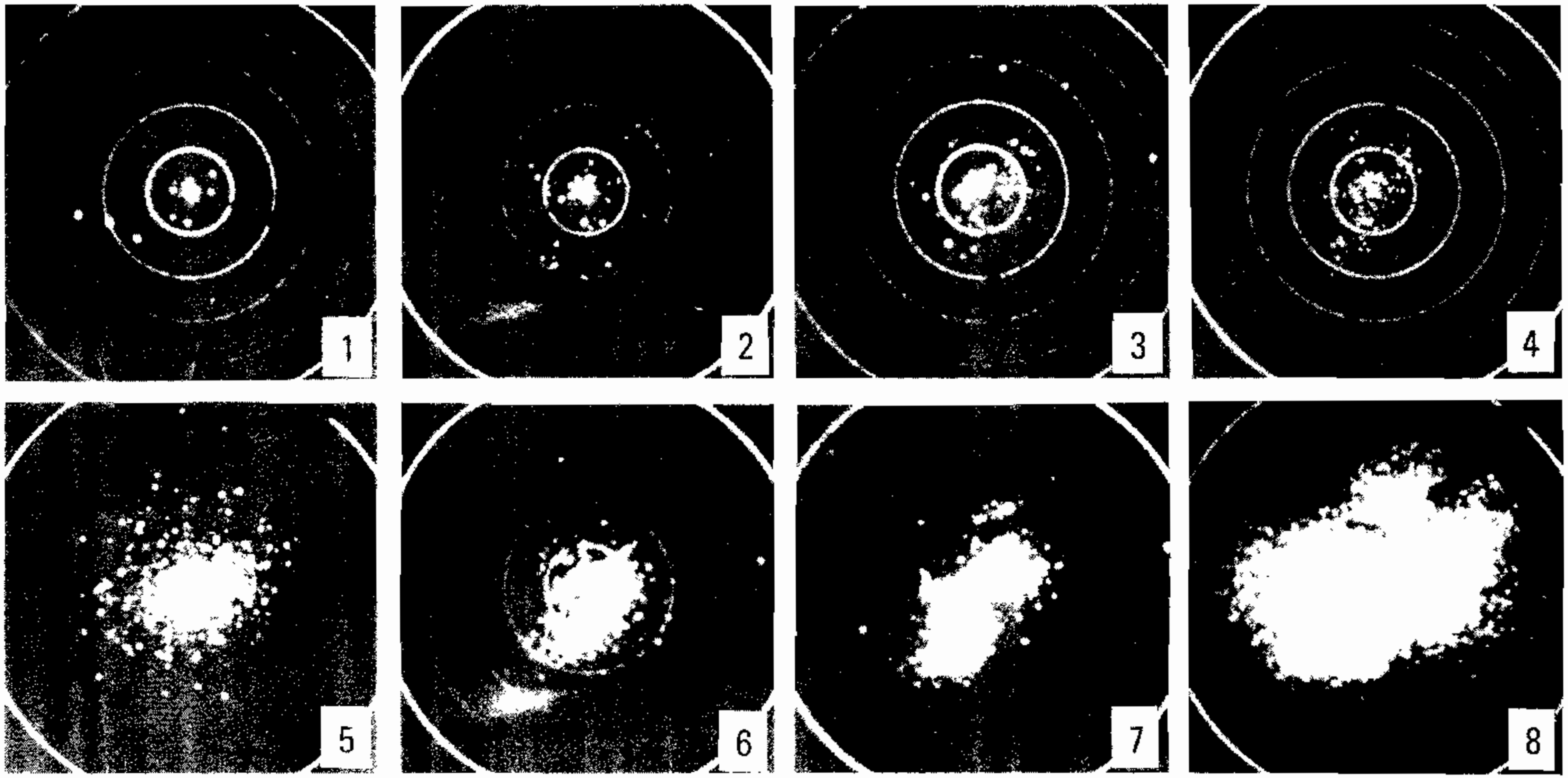


FIGURE 6. MIGRATION DENSITY SCALE

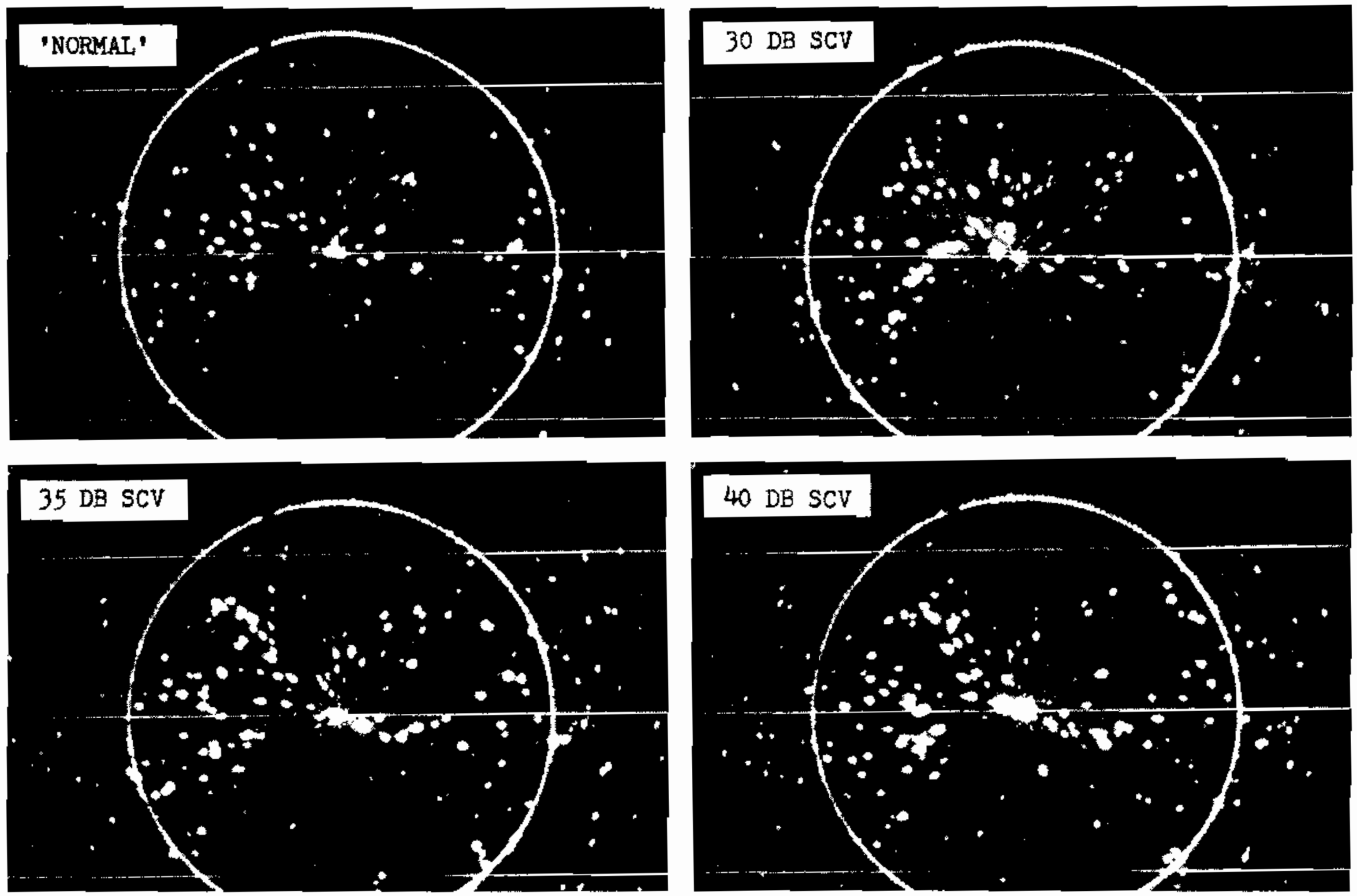


FIGURE 7. CHANGES OF ASR-5 MTI MODE

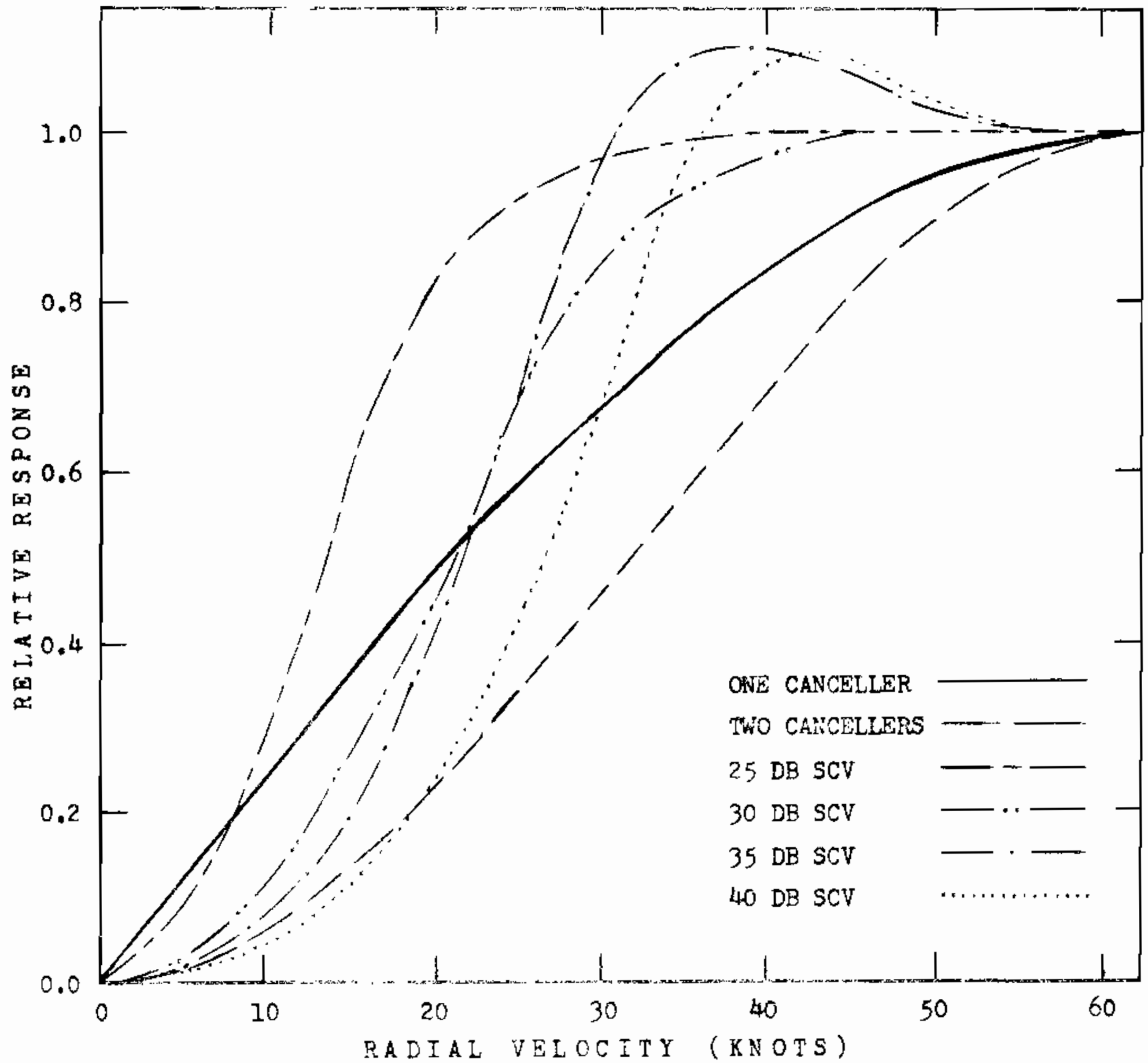


FIGURE 8. VELOCITY RESPONSE CURVES FOR ASR-5 MTI MODES

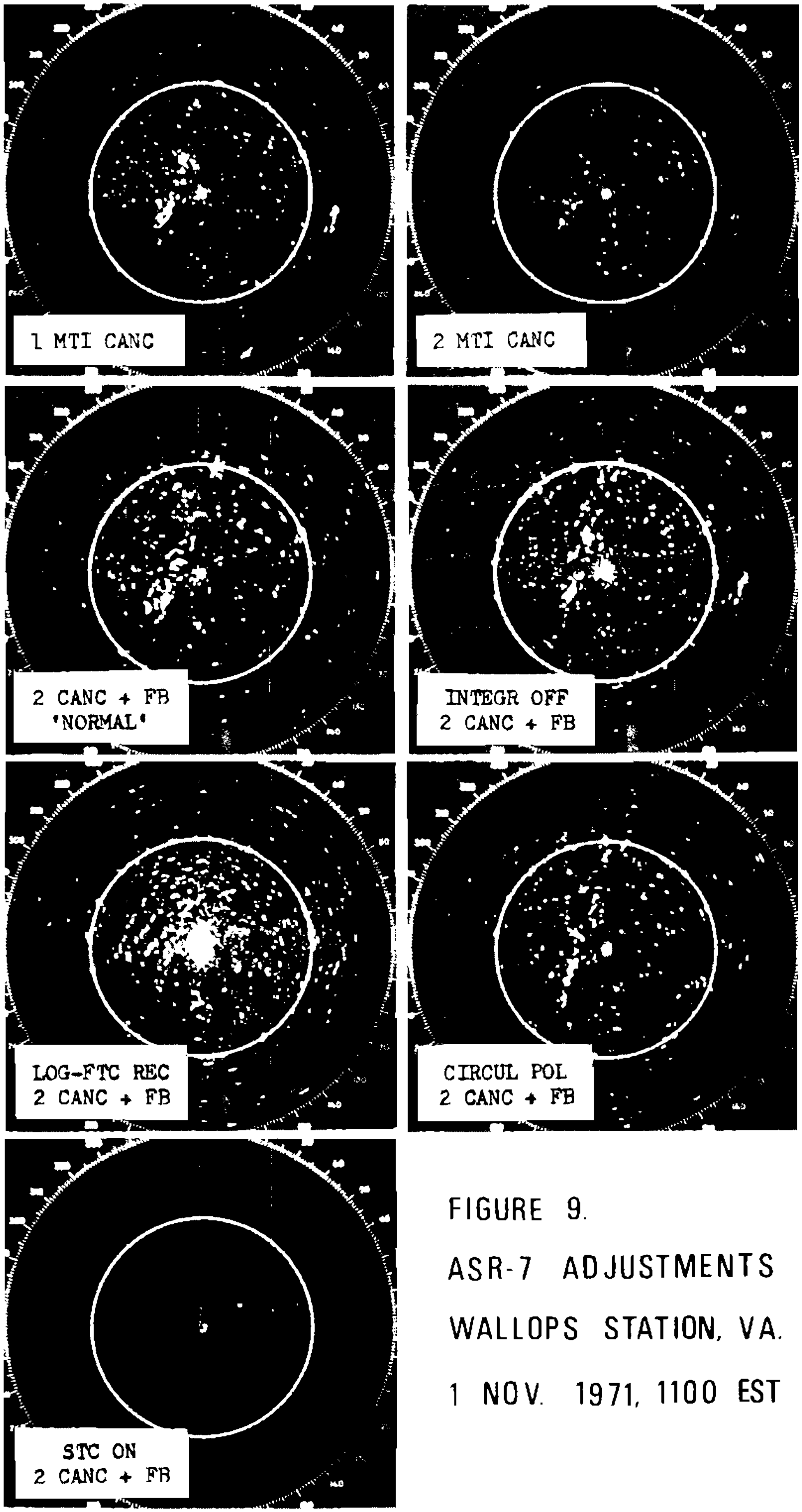


FIGURE 9.

ASR-7 ADJUSTMENTS

WALLOPS STATION, VA.

1 NOV. 1971, 1100 EST