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Radar Studies of Bird Migration

Final Report for Grant

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by

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INTRODUCTION AND CHRONOLOGY OF RESEARCH

Our observations of bird migration with NASA radars began at Wallops Island, Va. in the spring of 1969. These observations at Wallops continued until the fall of 1973. In addition from 1970 to 1973 we made simultaneous observations at a number of radar sites in the North Atlantic Ocean in a effort to discover what happened to those birds that we and others saw leaving the coast of North America headed toward Bermuda, the Caribbean and South America. Our research may thus be divided into two parts: first the studies of transatlantic migration, utilizing observations from a large number of radars, and second, more detailed studies of bird movements at Wallops Island. This report will, therefore, be divided into two parts.

PART ONE: TRANSATLANTIC BIRD MIGRATION

The regular, autumnal occurrence of large numbers of shorebirds over the western North Atlantic Ocean has been documented for at least two centuries (Wingate, 1973). Drury and Nisbet (1964) suggest that a number of warblers, in particular the Blackpoll Warbler (Dendroica striata) should be included as transatlantic migrants. This view is upheld by the observations of Wingate (1973) on Bermuda. Our aim has been to study the movements of birds with simultaneous observations from several radar sites on the

migration route, including radars on research vessels in the North Atlantic. A description of the radars which we used, the methods for obtaining and analyzing the data from radar PPI displays, a brief description of the patterns of migration at each site, sample photographs of the radar displays, and a discussion of the species probably involved in these migrations has been published in Williams, Williams and Ireland (1974). Bird movement over Bermuda has been reported in Ireland and Williams (1974). The present report will concentrate on those analyses of data made since these publications.

Patterns of migration

The general pattern of migration over the study area is shown in Figure 1. Observations at coastal and island radar sites are summarized by circular histograms showing the percent of nights of moderate to heavy migration in which the average direction of movement fell within a given direction. These circular histograms show two clearly different routes to the Caribbean and South America. For the first route birds move southwest along the North American coast, out along the Florida peninsula and then along the Caribbean islands to South America. For the second route, birds leave the North American coast heading south to east into the Atlantic and arrive at the Caribbean from the north and northeast. The direction of moderate and heavy migrations detected with our ship-board radars is also shown in Figure 1. These observations reveal that migration over the North Atlantic proceeds along a broad front rather than specific routes or leading lines. Our

Figure 1. Map of North Atlantic Ocean showing radar sites and principal directions of bird migration. Circular histograms at each radar site indicate percent of moderate and heavy migrations with average directions in 8 compass sectors. Ring in histograms indicates 50%. Arrows at sea indicate directions of moderate and heavy migrations observed with radars on ships.

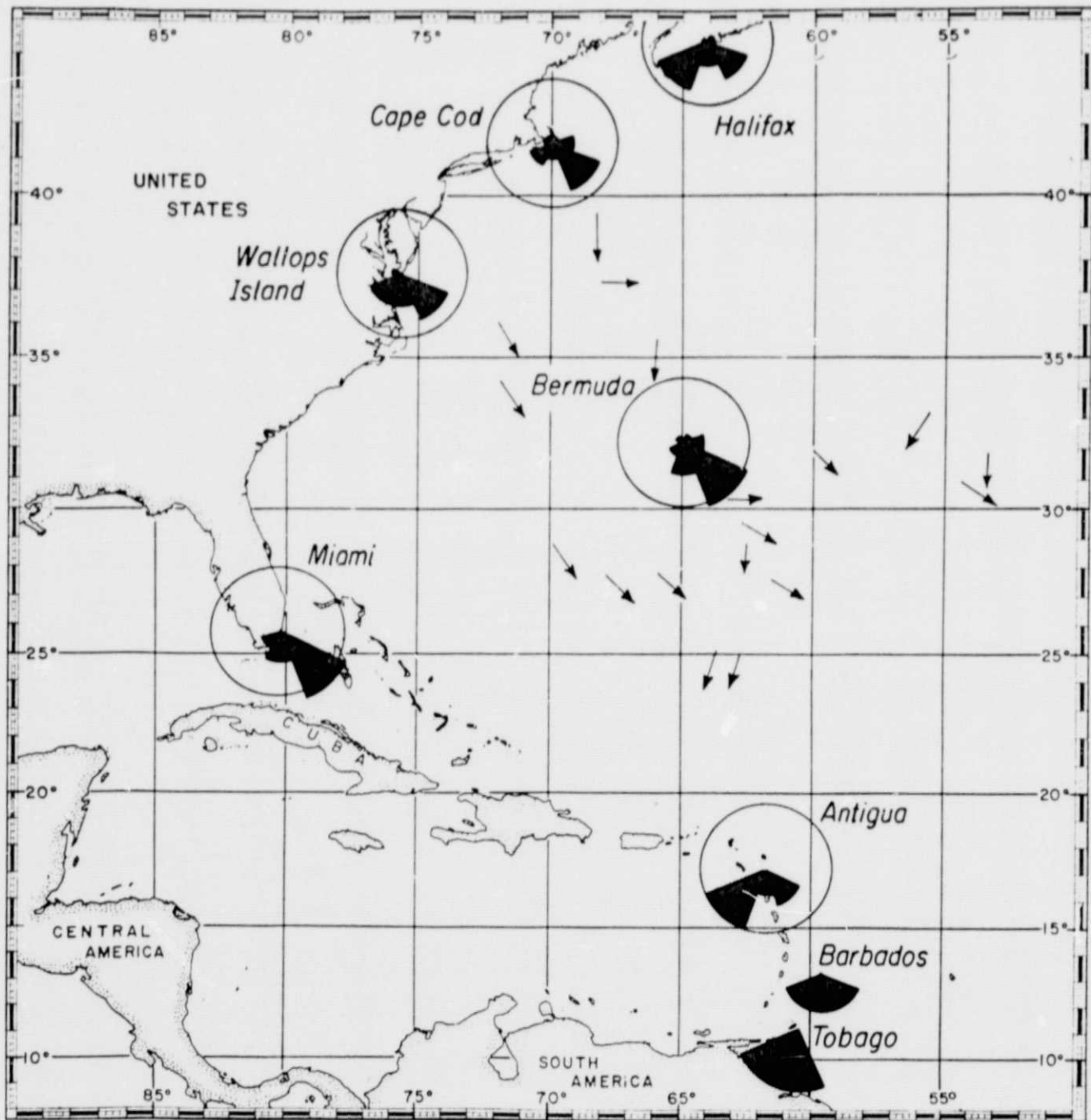


Figure 1.

Observations of migrations 1000 km east of Bermuda agree with reports from sailing ships in the 1850's of birds up to 900 km east of Bermuda (Hurdia).

Altitude of migration

Altitude of migration was greater at Barbados and Antigua than at other sites, as shown in Figure 2. Although both Richardson (1972) and Nisbet (1963) report some birds (probably shorebirds at 3,000 to 6,000 m, we did not often detect any significant numbers of migrants above 3,000 m at Cape Cod (height information was not available to us at Nova Scotia). Wallops Island, Miami, and Bermuda have altitudes comparable to each other with migration often reaching 3,000 m. The migration at Miami is remarkable in that the high targets were frequently of the diffuse, scintillating echoes attributed to passerine migrants by most observers (see Gauthreaux, 1971, and Drury and Keith, 1962) at altitudes below 2,000 m. Birds at Antigua and Barbados not only reached the greatest altitudes recorded for any known bird migration (6,500 m) but also on many occasions no birds were seen below 2,000 m (see also Hilditch, Williams and Nisbet, 1973). Tobago showed a sharp departure from the other Caribbean Islands, with all bird targets being at low levels. The high altitude movements over the northern Caribbean appear to be due to the presence of more favorable winds at altitudes above 2,000 m. The reduced altitude of birds at Tobago presumably indicates descent for landing.

Figure 2. Altitude frequency by radar site. Height of bar indicates per cent of moderate and heavy migrations in which birds were detected at a given altitude range.

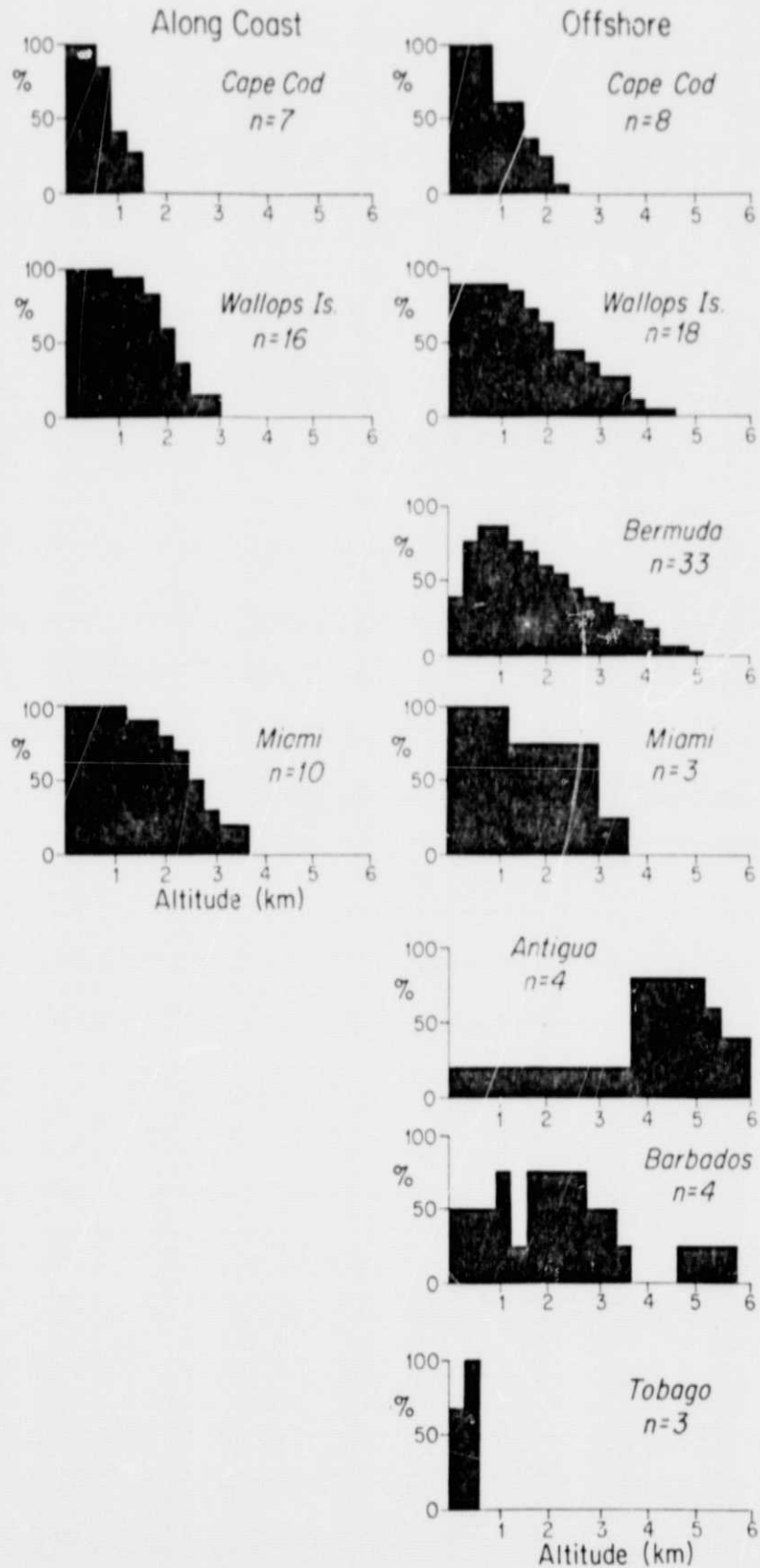


Figure 2.

Airspeeds

Figure 3 compares the airspeeds of migrants at all radar sites. Radars on the coast of North America revealed a greater spread of airspeeds than did radars in the Caribbean. If air-speed is assumed to be a more or less stable characteristic of a species, then the greater spread of airspeeds suggests, as would be expected, that coastal sites observe a greater diversity of species. The range of airspeeds for birds leaving the coast is reduced at Bermuda and further reduced in the Caribbean indicating considerable mortality en route.

Radar signatures

Figure 4 presents an analysis of radar signatures of bird targets leaving the North American coast at Wallops Island, at Bermuda (presumable en route), and (for a very small number of targets) at Antigua. These signatures and the airspeeds discussed above strongly indicate a mixture of fast flying shorebirds, having rapid, continuous wingbeats, slowly flying waders with slow wingbeats, and slowly flying passerines with rapid wingbeats often coming in bursts.

Timing of migration

Figure 5 presents the chronological relationship between radar observations at all manned radar sites for this study during 1971, 1972 and 1973. Migrations at each site are scored as light, medium or heavy. (This scoring may well not be comparable across different radars at different sites; a moderate migration at Halifax or Miami is probably as dense as a heavy

Figure 3. Airspeeds of birds detected during moderate and heavy migrations at all radar sites, except Halifax, N. S.

AIRSPEEDS

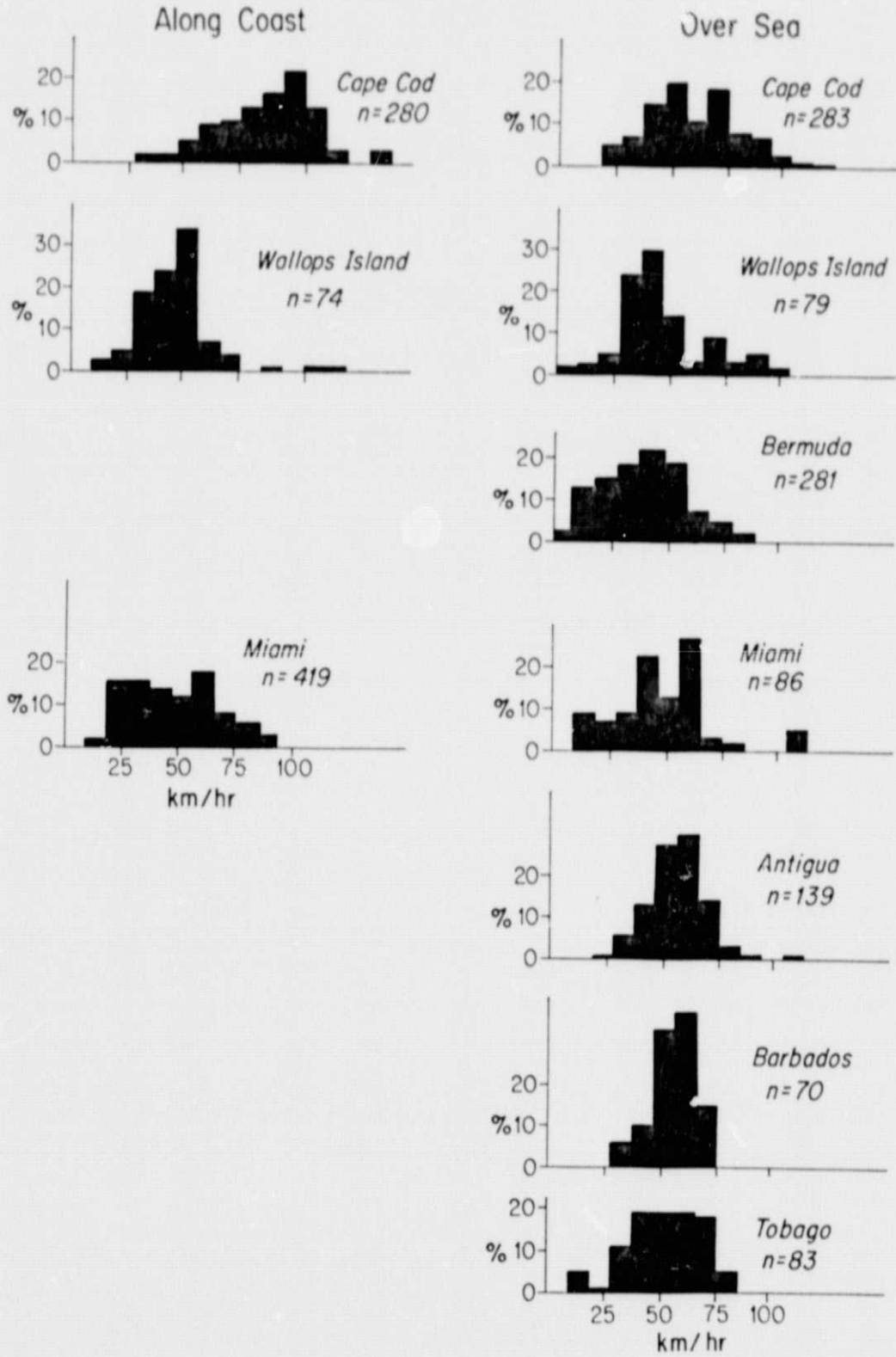


Figure 3.

Figure 4. Radar signatures off all birds detected at the three sites with tracking radars. Signatures are divided into three groups as described in text. Sample signatures are given below each group. Within groups signatures are divided by fundamental frequency of the radar signature. Height of bars indicate per cent of total signatures obtained at that site. The signatures obtained at Bermuda with fundamental frequencies above 24 Hz are at present unidentified. All were from records of low amplitude.

Radar Signatures

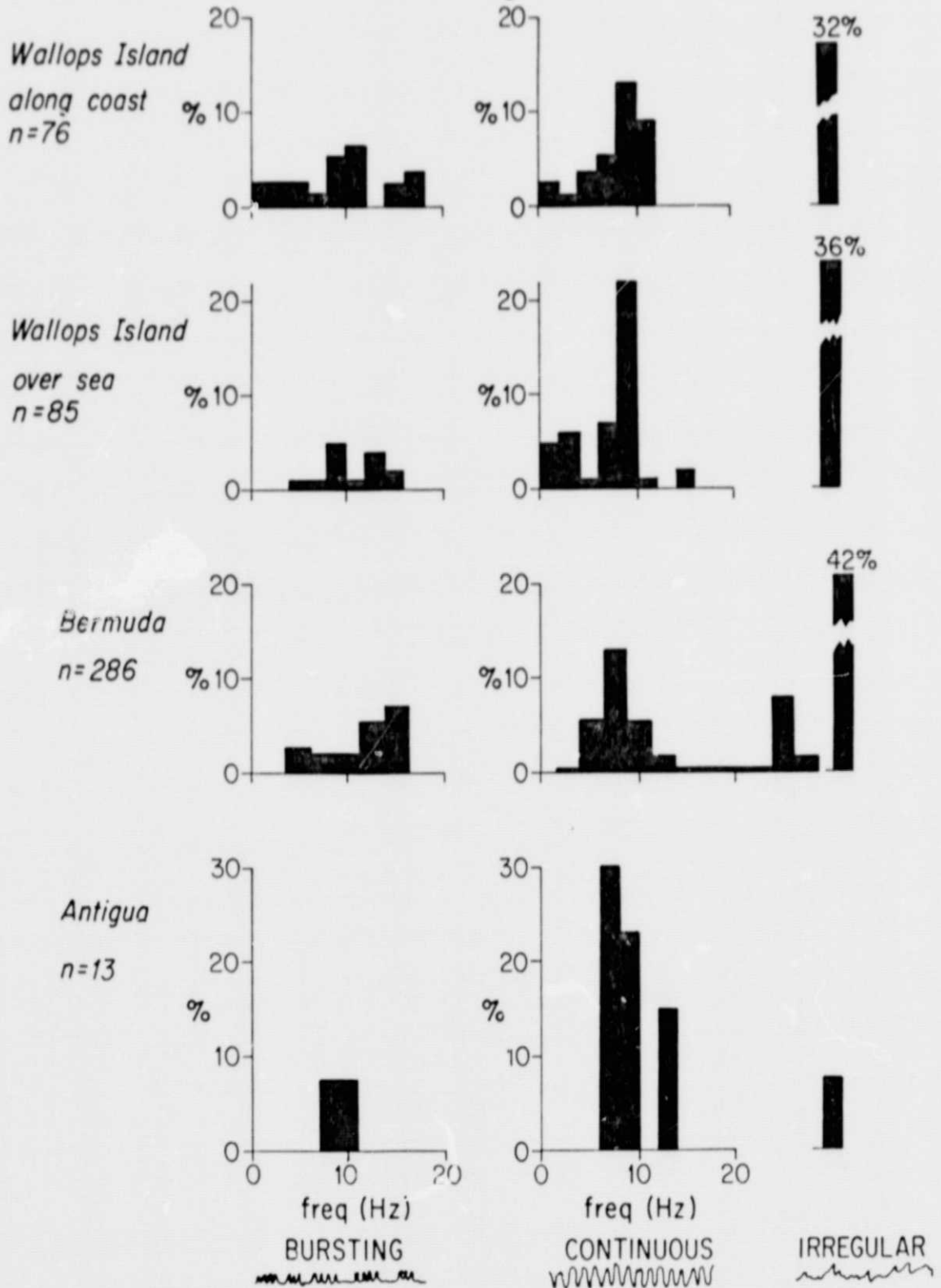


Figure 4.

Figure 5 . Average direction and density of bird migration over the North Atlantic Ocean as detected by radar. Light, moderate, or heavy migration is indicated by the width of the arrow. Direction of arrows shows the average direction of the most dense movement(s) seen during an 8 hr observation period. An arc between two light arrows indicates targets were spread between these directions. Weather symbols indicate prevailing frontal conditions between northern sites, and the presence of widespread rain (tropical depression) at Caribbean sites. Time is GMT. Rows labeled "weather" indicate the suitability of weather conditions along the North American coast for departures of migrants: - indicates weather favorable for departure (north winds, recent passage of a cold front), - indicates unfavorable conditions (south winds, cold front approaching, rain), and 0 indicates no clear advantage or disadvantage (stable high pressure system, light and variable winds). The symbol $\frac{-}{+}$ indicates favorable conditions on the northern part of the coast and unfavorable on the southern part.

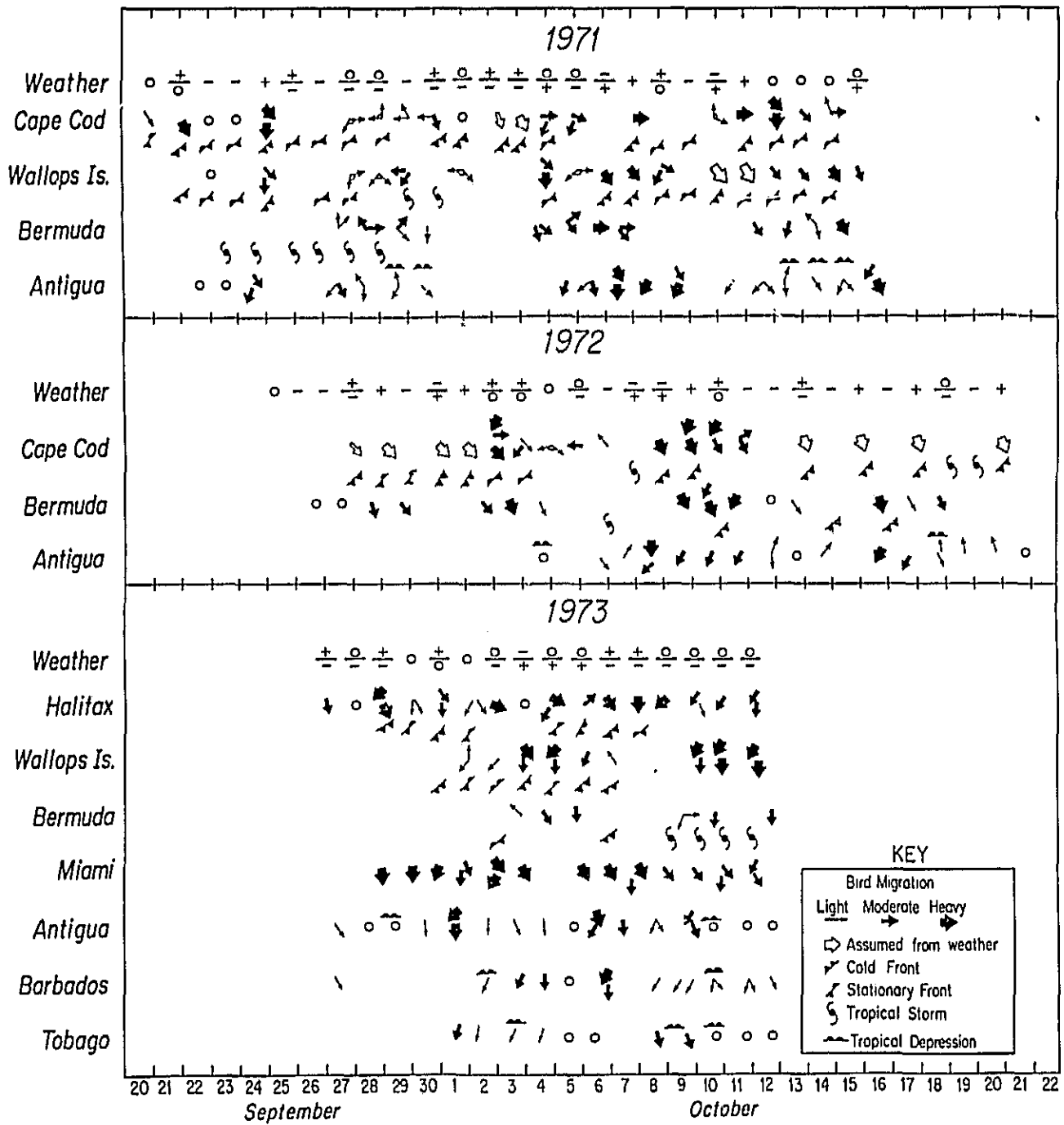


Figure 5.

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migration at Barbados.) The average direction of a bird movement is indicated by an arrow, and major factors in the weather are also shown. Inspection of Figure 5 reveals that for 19 of the 20 days on which moderate or heavy migrations were recorded in Antigua or Barbados, a moderate or heavy migration had departed the North American coast two or three days before. Since our observations were made during the day in the Caribbean, and by night (when most bird migration occurs) in North America, this means a flight time of 54 (minimum) to 74 (maximum) hours in most cases. The observations made at Antigua on 8 October 1972 are an interesting exception. A tropical storm prevented the movement of a cold front off the North American coast for a period of 6 days before these observations. The last night having suitable weather conditions for departure along the North American coast was the night of 4 October and our observations at Cape Cod indicated little offshore movement on this date. Thus, it appears that the birds seen on Antigua on 8 October may have been on the wing for as long as 102 hours. (The belief that at least some of these birds were passerines which could not rest on water is supported by the diffuse echoes typical of (nocturnal) passerine flights appearing on the Antigua radar on 8 October.)

Although the arrivals at Antigua and Barbados show a regular relationship to the movement of birds on the North American coast, it is interesting that not every major departure from the coast was detected at Antigua two to three days later.

Also the observations at all Caribbean sites do not agree. Moderate migrations at Barbados at times were not detected at Antigua or Tobago.

In some cases the lack of birds observed at any one Caribbean radar site appears to have been due to the birds avoiding areas of heavy rain associated with tropical depressions or easterly waves. Only in Tobago, and then only on two days, was the rain so widespread that it prevented observation of birds with the radars; in most cases it was possible to see a few birds flying in areas of the radar display not covered by rain cloud echoes. On such occasions significant numbers of birds were not detected at sites experiencing bad weather, even though birds were presumably in the general area, as shown by observations at other radars or by departures from the North American coast two to three days before.

Avoidance of bad weather is not, however, a sufficient explanation to account for all the instances in which moderate levels of bird migration were detected at some Caribbean sites but not at others. Instead, inspection of Figure 5 indicates that bird migration over the Atlantic is not evenly spread out over a very broad front but tends to occur as groups of birds perhaps a few hundred km across. Birds leaving the coast of North America typically show headings which vary by $\pm 40^\circ$. If each bird maintained its heading until it reached the Caribbean, the birds would be more or less evenly distributed over a front at least 2000 km wide. Since this does not appear to be the case, there must be some sort of communication

between birds or some common form of en route re-orientation.

Figure 5 also reveals a significant number of birds approaching the Caribbean islands from the northeast. The birds are not simply being blown by strong east winds but have air headings to the south or in some cases to the southwest (see Williams , Williams and Ireland, 1974). Since most migrations penetrate a cold front or stationary front (and thus encounter easterly winds) between Bermuda and the coast (see Figure 5) it is not possible for birds leaving the North American coast to approach the Caribbean from the east by maintaining a constant compass heading throughout their flight. Thus, we must conclude that avian migrants are capable of mid-ocean re-orientation based perhaps upon a celestial compass.

Summary

Both passerines and shorebirds appear to make regular autumnal migrations over the North Atlantic Ocean. The flight appears to take 54 to 74 hrs in most cases, although in one case a tropical storm may have prolonged the flight to 102 hrs. During these migrations the birds appear to maintain some degree of cohesion as opposed to purely random spreading, to be able to avoid areas of poor weather, and to re-orient their flight in mid-ocean.

PART TWO: TRACKING RADAR STUDIES AT
WALLOPS ISLAND, VA.

Our research at Wallops Island has focused on two major problems: developing and evaluating techniques for tracking birds with radars, and a study of the factors affecting individual migrant birds. Our techniques have been briefly reported in Williams, Williams, Teal and Kanwisher (1972) and more fully in Williams and Williams (1972). Techniques not covered in these papers will be discussed below under the appropriate subject heading.

TECHNIQUES

The reliability of radar signature parameters.

In much of our work radar signatures are used to distinguish different groups of birds. Despite three years of effort, it did not prove possible to get simultaneous film records and radar signatures of free flying birds. The maximum range for good optical work and the minimum range for good radar signatures (with the instruments we used) did not overlap. The records obtained by Bruderer and Jaquat (1972), and the technique of releasing captive birds from balloons or aircraft as used by Emlen (1974) and Vaughn (1974) appears to be more profitable. Their studies do not, however, answer questions concerning the variability over time of a signature for a single bird which has not undergone experimental trauma.

For this study we tracked free flying nocturnal migrants and recorded their radar signature once every five minutes as described in Williams and Williams (1972). Peak to peak time intervals were measured for each signature as follows: 10 adjacent

peaks, 10 cycles randomly selected within a 20 second record, and 10 cycles randomly selected from three 20 second records representing ten minutes of tracking. For birds in level flight, the three measures showed overlapping values indicating no systematic variation in signature over time. These data are shown in Figure 6. Thus it appears that relatively short radar signature records taken from free flying migrant birds may be taken as representative of that bird's radar signature.

Some birds show not only a constant fluctuation indicating wing beat frequency (Bruderer and Jaquat, 1972) but also alternating periods of activity and inactivity indicating periods of flapping and gliding flight. Bruderer and Steidinger (1972) suggested that the relative length of the active and inactive periods might be used for identifying bird targets. Our records (which for any one bird are much longer than theirs) indicate so much variability in this parameter that it appears to be of little diagnostic use. Furthermore, the relative length of flapping and gliding flight in our records shows a systematic variation with the rate of climb or fall of the bird as shown in Figure 7.

Chart records of radar signatures often show characteristic form with each successive cycle showing a repeating pattern of spikes or slow changes. It has been suggested that the shape of a single cycle might be used to identify birds. Our records indicate that such parameters vary greatly with the aspect of the birds and have little diagnostic value.

Figure 6 . Standard deviation of instantaneous radar signature frequency vs average frequency. Dotted lines encircle data from one or two birds. Each data point indicates the standard deviation and mean for ten cycles. Cycles were measured from 10 successive beats, 10 cycles selected at random from a 20 second continuous record (triangles), and 10 cycles selected at random from all available records for that bird (crosses).

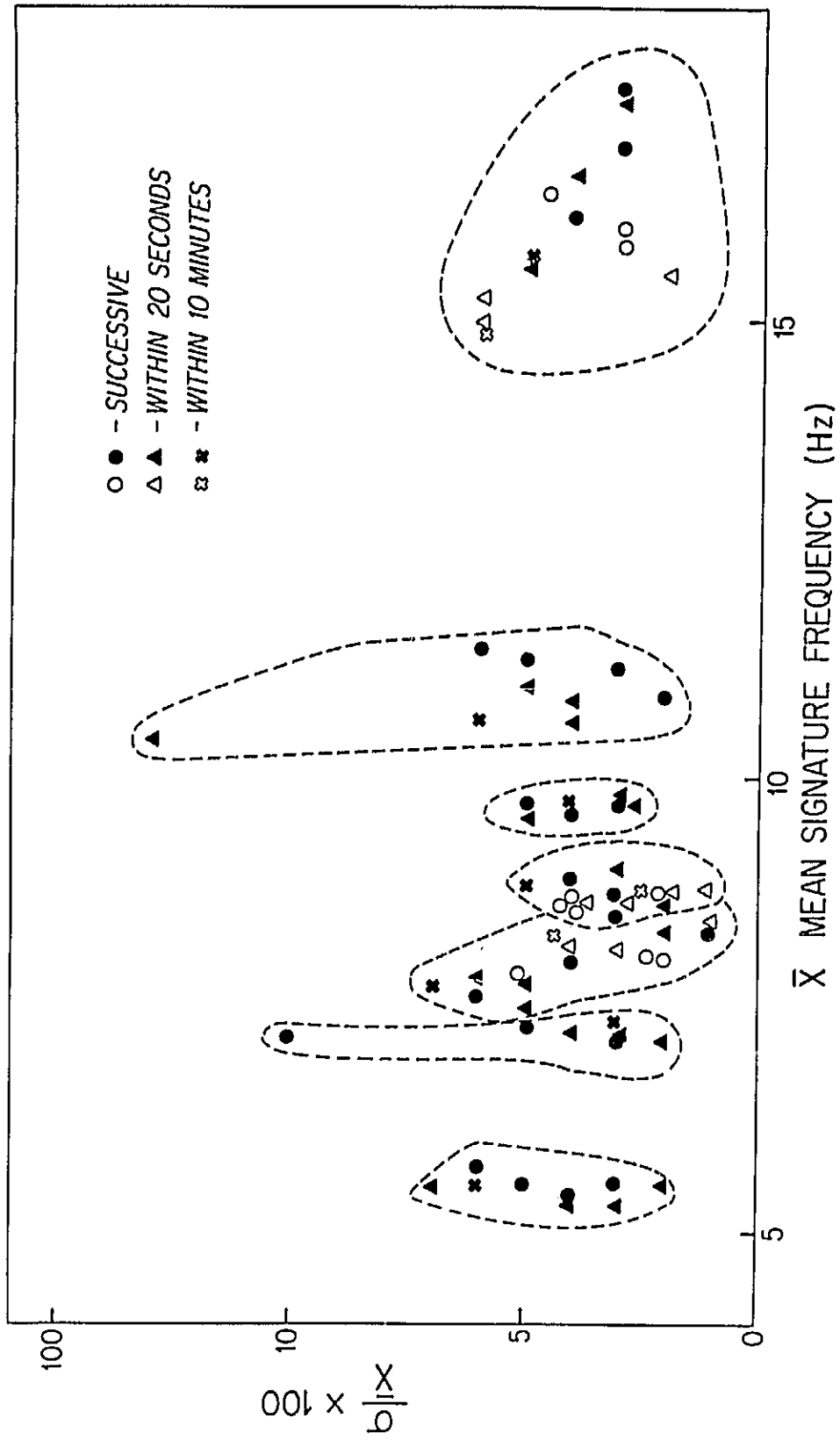


Figure 6.

Figure 7 . Duty cycle of bursting signatures vs rate of climb or fall. Data taken from records of 5 birds which showed clear changes in rate of climb during tracking. Per cent of time beating refers to the active phase of the "bursting" signatures. See Figure 4 for example of this type of radar signature.

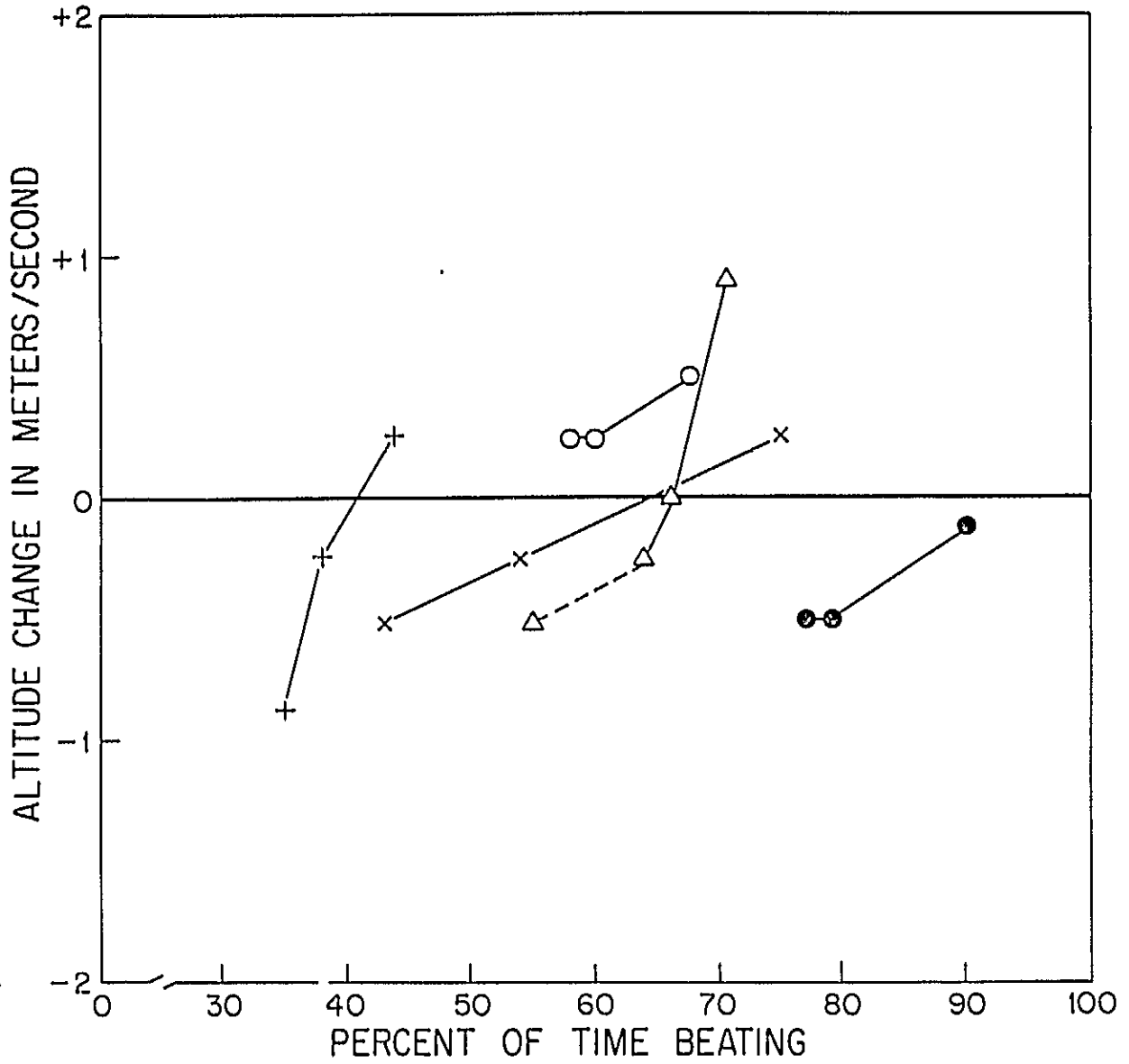


Figure 7.

The variance of fundamental frequency of some signatures was consistently less than in others (see Figure 6). This variance itself may be of importance in the analysis of radar signatures of bird targets, and suggests that investigators obtaining signatures of identified birds consider this parameter as an aid to identification..

Accuracy of tracking

Direct measurement of the accuracy in tracking very small objects, such as birds, does not appear possible, as we have no other technique than radar for measurement of the position of the bird in space. Tracking unknown objects such as aircraft does not appear to be comparable to tracking a small target which can fluctuate by three orders of magnitude in cross section (see Konrad et al., 1968). Plots of the same bird tracked with two radars can be superimposed in altitude and horizontal position, but errors caused by refraction of the earth's atmosphere could affect both radars equally.

Density measurements

Most measurements of the density of bird migration (Eastwood 1967, Nisbet 1963, and Gauthreaux 1970) seek to determine the total number of birds over a given area of land or the total number of birds crossing a mile of "front" per hour. For design of aircraft to withstand birdstrikes, or routing of aircraft around areas of hazardous concentrations of birds a more useful measure is the number of birds in a unit volume airspace. To determine this factor the performance diagram of the SPANDAR

radar was calculated from the measured antenna pattern for a target cross section of 100cm^2 (the approximate cross section for birds large enough to be hazardous to aircraft (Konrad et al., 1968)). PPI photographs were made as described in Williams and Williams, (1972) at various angles of elevation, ^{and} the number of targets on the photographs were counted between 3.7 km range rings. 18,283 targets were counted in 15 PPI photographs. The volume of the sector swept out by the radar beam was then computed to give the density of bird targets. Figure 8 presents the relationship between altitude and the computed density of migrant birds. The striking increase in density at low altitudes is not simply a function of range as measurements were taken at several angles of elevation. Further refinement of this technique is possible by obtaining an estimate of the distribution of radar cross sections of targets and then more accurately computing the volume of the radar beam for differing cross sections.

The effect of radar energy on migrant birds.

Birds did not give a statistically significant reaction to illumination by a beam of radar energy by changing course or speed as they approached the radar. During 1971 three birds which passed close to the radar were suddenly subjected to a burst of full transmitted power by the SPANDAR. None of these birds significantly changed course, altitude or flight speed. Peak power densities experienced by the birds ranged from 115.9 mw/cm^2 to $.021\text{ mw/cm}^2$.

Figure 8 . Density of radar targets vs altitude (semi-log plot). Data taken with the SPANDAR at Wallops Island, Va. Each line represents data from a different PPI photograph.

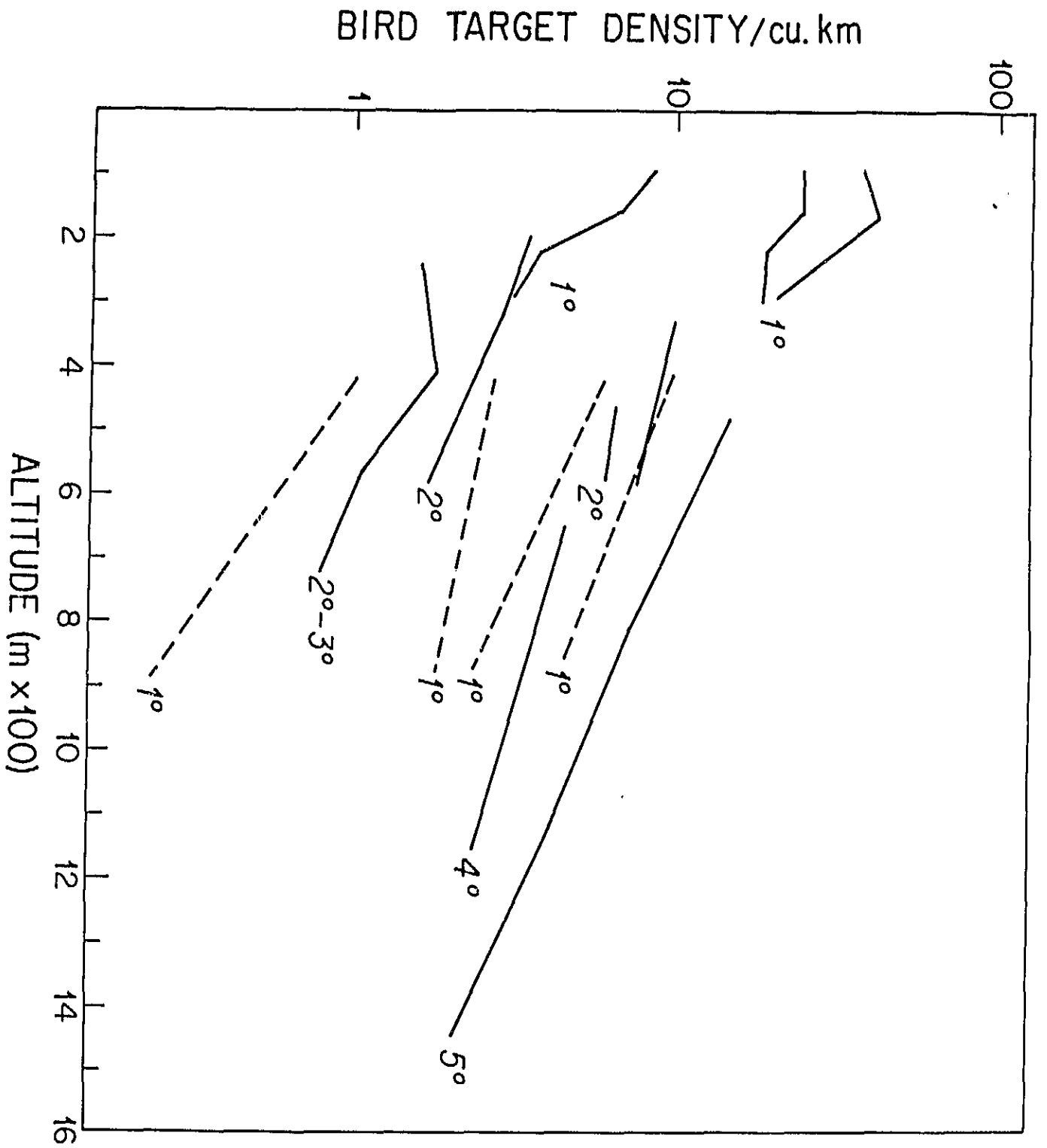


Figure 8.

FACTORS AFFECTING AVIAN MIGRANTS

From March 1969 to November 1973 we obtained over 600 tracks of bird targets with the SPANJAR, the FPS-16 and the MPS 19 radars at Wallops Island, as described in Williams and Williams (1972). Of these tracks we have selected 402 for analysis (all lasting for more than 5 minutes, and without errors in data recording). Data for each track were put on Keysort cards for a preliminary examination preparatory to a full scale computerized analysis of the data. Below we report the results of the analyses using the Keysort cards.

For each track we scored and punched onto the cards the following items: density of migration (light, moderate, or heavy); the altitude of the migrant; the rate of climb or fall; the direction (ground velocity) of the migrant with respect to the coast line (up, down, out to sea, or inland); the signature of the target coded by fundamental frequency and type of signature (continuous, bursting or irregular); the time of day; the time of year (spring, early fall and late fall); whether or not clutter (weather) was recorded frequently while tracking; the velocity of the wind; the angle of the wind and the bird's heading (crosswind, headwind, or tailwind); cloud cover; and the air velocity of the bird. Comparisons were made between categories with Chi Square tests. (Unless stated, all probabilities are less than .01.)

Altitude of migrants Although Bruderer and Steidinger (1972) report greater airspeeds for high birds than those near the earth, we found no significant relationship between altitude and airspeed. Cloud cover greater than 9/10ths overcast

produced lower altitude migrations, and birds flying out to sea (away from the coast) were higher than birds flying along the coast. Birds tracked before sunset and birds tracked during light or moderate density migrations were lower than those tracked after sunset or during heavy migrations (although this may be an artifact of our selection procedures which favored low flying birds by day and avoided the altitudes which had densities of birds so great that we could not track for more than a few minutes). The percentage of birds which showed rates of climb or fall greater than .3 m/sec was not affected by cloud cover and tended to be greater before sunset than after. Comparison of rate of climb and the altitude at the time of tracking showed the surprising relationship ($p < .05$) that birds above 3,000 m tended to be climbing while those below 3,000 m tended to be falling. Obviously this condition cannot persist for an entire night, but may be characteristic of the pre-midnight hours when we tracked birds. Major parts of our analyses were concentrated on two topics: the accuracy of orientation of birds and the comparison of migratory behavior and radar signatures. Accuracy of orientation was defined as the ability of birds to fly in a straight line. Two measures of straightness of track were used: the standard error of estimate of the track with reference to a straight line, and the ratio between actual path length and the shortest path length. These measures, called "error", were not significantly associated with altitude, "weather" in the tracking zone, cloud cover or airspeed of the targets. Wind speeds of 21 to 32 km/hr resulted in much higher

errors than did either lower or higher windspeeds. Presumably the lower speeds did not affect flight, and at the higher speeds only the largest migrants were aloft. Headwinds produced the highest errors and tailwinds were associated with low errors. Errors in flight orientation thus appear to be due primarily to simple air turbulence rather than visibility or altitude.

Radar signatures. The possibility of identifying birds by their radar signatures has been one of the primary reasons for utilizing tracking rather than search radars. It is apparent from both radar and visual studies (see Eastwood 1967) that different birds use different migration strategies, but it has not been possible to identify migrants aloft. We believe that our analyses represent a step in that direction.

All radar signatures were first divided into thirteen categories. These thirteen groups were then compared with respect to the variables given at the beginning of this section. Analysis of these comparisons revealed that some of the thirteen groups appeared to react in the same way for all variables examined. In other words, it appeared possible to group radar signatures of birds so that each group appeared to have a coherent migration strategy.

At the present time we have reduced our analysis to 6 groups tentatively identified as follows: "bursting" with frequencies of 1 to 6 Hz ("gulls"); bursting with frequencies of 6 to 20 Hz ("passerines"); continuous with frequencies of 1 to 6 Hz ("waders"); continuous with frequencies of 6 to 10 Hz ("waterfowl-shorebirds"); continuous with frequencies of 10 to

20 Hz ("shorebirds"); and irregular signatures ("flocks"). Signatures (except "flocks") obtained in the spring were 24% "passerine", 4% "gulls", 35% "waterfowl-shorebirds", 4% "waders", and 2% "shorebirds". Signatures obtained during the early fall showed 6% "gulls", 35% "passerine", 18% "waders", 42% "waterfowl-shorebirds" and 9% "shorebirds". Late fall migrants were 52% "passerine", 2% "waders", 39% "waterfowl-shorebirds" and 5% "shorebirds". Between these groups there was no significant difference in rate of climb or fall, error, or preference for clear or overcast skies. The "waterfowl-shorebird" groups showed high airspeeds (40-60 km/hr) and the "passerine" group showed lower (20-30 km/hr) airspeeds supporting our tentative classification. The "shorebird" and "wader" groups, however, showed a tendency toward slow flight, suggesting a re-examination of these categories. In comparing type of signature and density of migration as determined from PPI photographs, we find that the "waterfowl-shorebird" and "shorebird" groups tended to predominate during heavy migrations, and the "passerine" group to be found most often during light and moderate migrations ($p < .05$). (This is probably due to our inability to track birds for more than a few minutes within dense passerine migrations. During heavy passerine migrations we tended to select offshore targets at great altitudes as mentioned above.) Flocks of birds tended to fly before sunset and single birds after sunset.

Two major factors in the strategy of migration are the preferred flight direction and the response to winds. Flocks of birds and the "gulls" group tended to move parallel to the coast,

and the "waders" and "waterfowl-shorebirds" tended to move away from the coast ($p < .05$). This becomes more significant when one considers the air headings of birds. The "gulls" were concentrated in the sector 180° - 225° , as were the "passerines". The "waders" had widely distributed air headings, as did the "waterfowl-shorebirds" group (the latter having a tendency toward headings in the sector 135° - 180°). Movement along or away from the coast (actual track of birds) is the resultant of the birds' air velocity and the velocity of the wind. Thus, the analysis of winds aloft indicates that the reason "passerines" failed to show a clear preference for movement with respect to the coast despite preferred SSW air headings was that they tended to fly in west winds which drifted them offshore. The offshore movement of "waterfowl-shorebirds" and "waders" was in large part due to their preference for west winds. Flocks and "gulls" preferred north winds which aided their movements down the coast.

Birds also showed a preference for certain wind speeds. This was one of the few areas in which there was a clear difference within the "passerine" group with birds having signatures of 6-10 Hz preferring winds above 30 km/hr, and "passerine" birds with signatures above 10 Hz preferring winds less than 30 km/hr. Despite their high air speed the "waterfowl-shorebird" group did not show any significant preference for high windspeeds. The "shorebird" group showed a strong preference for winds less than 30 km/hr. When the data for all seasons were summed together there was no significant relationship between signature groups and head, tail or crosswinds. However, the fall tracking data

taken alone did show a significant difference with the low frequency signatures "gulls" and "waders" accepting headwinds and crosswinds, the "waterfowl-shorebird" and "shorebird" groups preferring tailwinds, and the "passerines" distributed as would be expected by chance.

Taking all available information, we can describe the tentative groups as follows: the "gulls", a group of low wingbeat rate, "bursting" signatures, moderate to fast flyers (20 to 60 km/hr), tending to move parallel to the coast with tailwinds and air headings to the SSW. This group may well include the largest passerine birds, Gannets, and the large Herons, as we have seen Great Blue Herons pausing in flight to glide while on migration over Bermuda. That the "passerine" group represents a coherent migratory strategy despite a wide range of wingbeat frequencies agrees well with deductions from observations of grounded migrants. This group is divided only in preference for certain wind speeds with the larger birds (lower wingbeat rate) appearing to tolerate higher winds. They tend to have low air speeds, and air headings to the SSW, but due to drift by winds many move offshore. Contrary to the findings of Gauthreaux and Able (1970) and Able (1974), there was no evidence that the passerines tended to fly with the wind (had tailwinds). The "waders", a group of low wingbeat rate, predominantly low airspeed birds, tended to move offshore with west winds and a slight concentration of east air headings but often flying with a crosswind. This group is probably diverse, and in addition to the waders may contain some birds listed under "gulls" and the largest waterfowl.

The "waterfowl-shorebird" group is certainly diverse and we hope to further divide this group by some parameter into its component parts. These birds show high airspeeds, and are the most frequent bird tracked during heavy migrations (due to our selection bias, in part). They moved away from the coast on west winds with air headings generally to the east of those taken by "passerines", usually flying with the wind. The "shorebird" group appears to be the most difficult to identify with any known migration routes. These birds with rapid wing beats and low airspeeds were often associated with heavy migrations and light north winds. They moved south in fall (and were absent in spring), being equally distributed between offshore and along the coast categories and accepting tail or crosswinds.

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