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RADAR INVESTIGATIONS OF THE BAT HAZARD TO HIGH PERFORMANCE AIRCRAFT AT RANDOLPH AFB, TEXAS

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Final Report

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Air Force Systems Command
Kirtland Air Force Base, NM 87117

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During the months of April through October, Mexican free-tailed bats (Tadarida brasiliensis mexicana) are a major cause of T-38 engines failures at Randolph AFB, Texas. The airborne behavior of T.b. mexicana emerging from and returning to the Bracken cave, near Randolph AFB, Was observed with both search and height-finding radars. Radar echoes from dense groups of bats covered areas as large as 500 km^2 and rose to altitudes of over 3,000 m. Evening bat flights appeared to have three distinct phases of development; exit from the roost → OVER

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and ascent, transition to level flight, and dispersal. In the dispersal phase, the bats usually traveled directly toward Randolph AFB. Bat flights may be grouped into three types on the basis of their vertical distribution. One type, characterized by flight at low altitude, was usually observed on nights when T-38s were damaged. A bat avoidance program, based on real time radar observations, was initiated at Randolph AFB during the summer of 1971 and continued thru 1974. Since the start of the program, the frequency of strikes has decreased. It appears possible to predict nights when bat strikes are most likely to occur 24 hours in advance. Stobe lights were found to be an ineffective bat deterrent.

PREFACE

We are deeply indebted to the many members of the USAF and the FAA who assisted us in this research. We especially wish to thank the men of the 12th Flight Training Wing Flying Safety Office, the 24th Weather Squadron, and the 2015th Communications Squadron. Without the interest, advice, and cooperation of these men, the project would not have been possible. The data presented in this report were collected in 1967 and 1968 under AFOSR Grant No. 4260-67-0063 to T. C. Williams, in 1971 and 1972 under AFOSR Grant No. 71-2123 to T. C. Williams, as well as in 1974 under AFWL/AFOSR Contract No. 73-187. Lawrence Guzy, Christopher Hilditch, and Thomas Klonowski aided in the collection of data. Robert Babcock, Judy Brand, and Carol McClintock assisted with data analysis. We thank Helen Poole for typing the manuscript.

CONTENTS

ILLUSTRATIONS

TABLES

SECTION I

INTRODUCTION

THE RANDOLPH AFB BAT PROBLEM

The ever-increasing use of high performance USAF aircraft has resulted in a rising number of collisions with flying wildlife (Ref. 1). These collisions cause millions of dollars damage to USAF aircraft each year and have been responsible for several fatal accidents. Within the continental United States, the frequency of such collisions or strikes varies with geographical location. Almost 50% of the USAF strikes recorded each year occur in the southwest (Ref. 2).

An unknown percentage of these southwest strikes involve bats rather than birds. Bats are a major cause of aircraft engine failures at Randolph AFB near San Antonio, Texas (Refs. 3-4). Randolph AFB is a major USAF flight training facility.

The evidence that bats are a hazard to aircraft operating from Randolph AFB comes from two sources. The first concerns the seasonal and daily timing of the collisions. Figure 1 shows the average number of both damage and nondamage bird and bat collisions per month at Randolph AFB during 1966 and 1967, the two years prior to the introduction of any bat avoidance procedures. Note that there are many strikes during the summer months as well as in the spring and fall when large numbers of migrant birds pass through the San Antonio area, and when the greatest number of strikes would normally be expected. This yearly pattern of strikes is not surprising. Large numbers of bats are present in the San Antonio area each year from April through October. Further, the majority of strikes at Randolph AFB occur at times

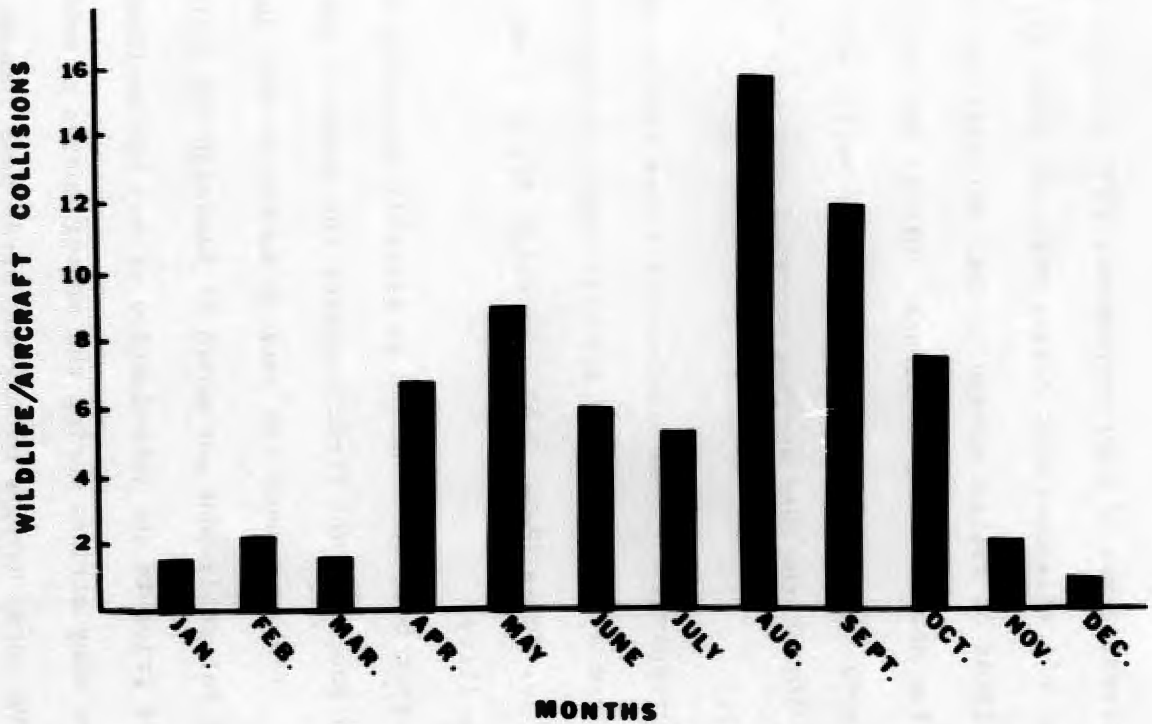


Figure 1. The average number of damage and nondamage bat and bird strikes per month at Randolph AFB, Texas during 1966 and 1967, the two years prior to the introduction of any bat avoidance procedures.

of day when bats are active (see Section V).

The second and more direct line of evidence comes from the identification of bat remains following strikes. The aircraft most frequently damaged by bats is the Northrop T-38 Talon trainer shown in figure 2. Bat strike damage to other types of aircraft operating from Randolph AFB is rare and usually minor. The records of the 12th Flying Training Wing Safety Office at Randolph AFB indicate that, from 1966 thru 1974, 34 T-38 engines were damaged by bats. In all cases (18) where the species of bat was identified by personnel at the Bird and Mammal Laboratories of the U.S. Department of the Interior, the collisions were found to involve Mexican free-tailed bats (*Tadarida brasiliensis mexicana*). Further, it is highly probable that many of the 62 T-38 engines damaged by unidentified flying animals at Randolph AFB from 1966 thru 1974 were also damaged by bats (see Section V).

Approximately 92% of the bat strikes and collisions with unidentified flying animals from 1966 thru 1974 occurred within 12 km of Randolph AFB, while aircraft were taking off, landing, or in the traffic pattern. The majority of these strikes (90%) took place at altitudes below 350 m. Collisions at altitudes of up to 2,000 m have been reported. Bat/aircraft collisions appear to be a problem unique to the San Antonio area.

THE MEXICAN FREE-TAILED BAT

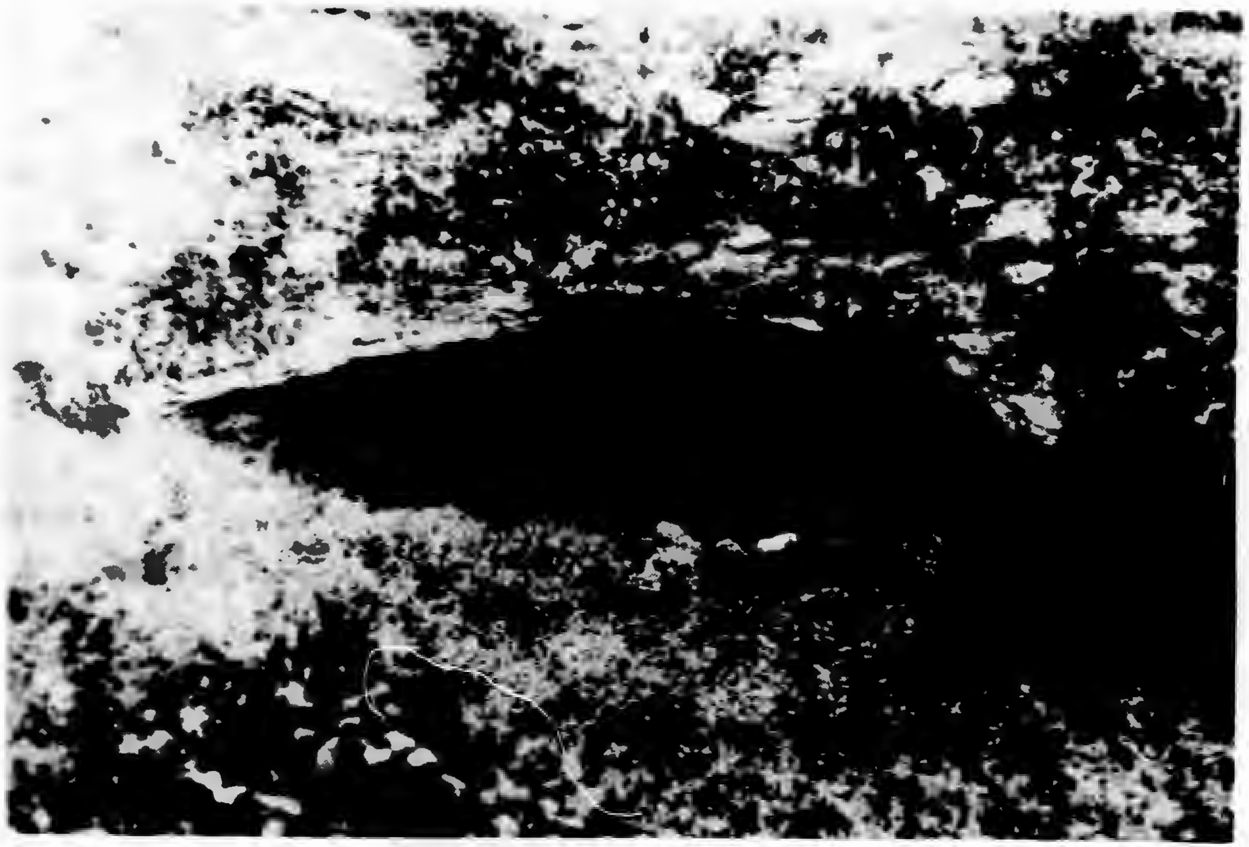
Mexican free-tails winter in Mexico, migrating to the southwestern United States each spring (Refs. 6-8). The bats usually arrive in Texas in large numbers in early April, and establish roosts in several caves along the Balcones escarpment to the north of San Antonio. The population within a single cave has been estimated to reach 20 million animals (Refs. 9, 10). One of the largest of these caves, the Bracken cave, is located 18 km NNW

Figure 2. A USAF Northrop T-38 Talon jet training aircraft.

of Randolph AFB, almost directly in line with the base runways. The entrance to the bracken cave is shown in figure 3.

Each evening the bats leave the caves to forage for insects. Figure 4 is a photograph of bats leaving the vicinity of the Bracken cave. The sound produced by millions of Mexican free-tails leaving a large roost has been compared to the roar of a white-water river (Ref. 8). The bat flight appears as a dark cloud in the sky which is often visible for several km. The bats frequently travel away from the caves in dense formations resembling serpentine columns. These columns travel parallel to the ground at altitudes of 200 m or less, for distances of up to several km, and then ascend, rising out of sight of ground observers. In the morning, the bats often assemble in dense formations before returning to the caves. Young bats are born in June and most are capable of flight by early August, a fact which may explain the August peak in strikes shown in figure 1. Migration back to Mexico usually begins in September and few bats remain in Texas caves by the middle of December (Ref. 8).

Bats from the Bracken cave may consume more than 5 tons of insects during a single night, many times the number destroyed by any human insect control program (Refs. 3, 8). Bats are, therefore, of considerable enonomic importance in the San Antonio area. Neither the destruction of bat populations nor the closing of bat roosts are viable solutions to the bat strike problem. Attempts to keep the bats within the cave until nighttime flying operations are completed are also inadvisable. Mexican free-tailed bats have been found to be highly sensitive to such disturbances, often abandoning a cave for alternate roosts at the slightest provocation (Ref. 11). Any disturbance of the population in the Bracken cave would quite likely result in large numbers of bats seeking alternate roosts in buildings in the surrounding



<u>Figure 3</u>. The entrance to the Bracken bat cave. The cave is located approximately 18 km NNW of Randolph AFB. During peak periods, the cave may house as many as 20 million Mexican free-tailed bats.

<u>Figure 4</u>. An evening flight of Mexican free-tailed bats photographed near the Bracken cave.

community, including buildings on Randolph AFB.

RESEARCH ON THE BAT HAZARD TO AIRCRAFT

For the past several years, we have worked closely with the 12th Flying Training Wing Flight Safety Office at Randolph AFB in devising procedures for reducing the bat hazard to aircraft. The information contained in this report was collected in 1967, 1968, 1971, 1972, and 1974. This manuscript summarizes our techniques for collecting data on bat flights with radars, describes our findings concerning the vertical and horizontal distribution of bat flights and how these variables are related to the frequency of bat strikes, describes the operation of a bat avoidance program based on real time radar observations, summarizes our progress toward predicting evenings when bat strikes are most likely to occur, and describes the results of our experiments concerning the bat deterrent properties of strobe lights.

SECTION II

MATERIALS AND METHODS

RADARS

For an excellent review and discussion of the techniques used to detect flying wildlife with radars and the procedures employed to make permanent records of radar data, consult references 12, 13, and 14. The following cites only the specific techniques and procedures used in our research.

Figure 5 shows the location of the radar installations used to observe bat flights, the approximate maximum range at which each radar could detect bats, and the location of several caves near Randolph AFB housing an estimated million bats or more.

Three types of radar were employed: search, height-finding, and weather. Three search radars were used to obtain information on the horizontal distribution of bats: a 10 cm wavelength, 400 kw peak power, ASR-6 approach control radar located at San Antonio International Airport; a 10 cm, 100 kw, MPN-14 approach control radar located at Randolph AFB; and a 23 cm, 5 Mw, FPS-91-A surveillance radar located at Lackland AFB. The FPS-77 weather radar at Randolph AFB (5 cm, 250 kw) provided information on the vertical distribution of bat flights. Data on the altitude of bats flights were also obtained from the FPS-6 height-finding radar at Lackland AFB (11 cm, 4 Mw).

The FPS-91-A search radar was used to gather information on the overall pattern of bat activity in the San Antonio area. Due to the proximity of the Bracken cave to Randolph AFB, the majority of our observations were made on bats emerging from and returning to this roost. The ASR-6 approach control

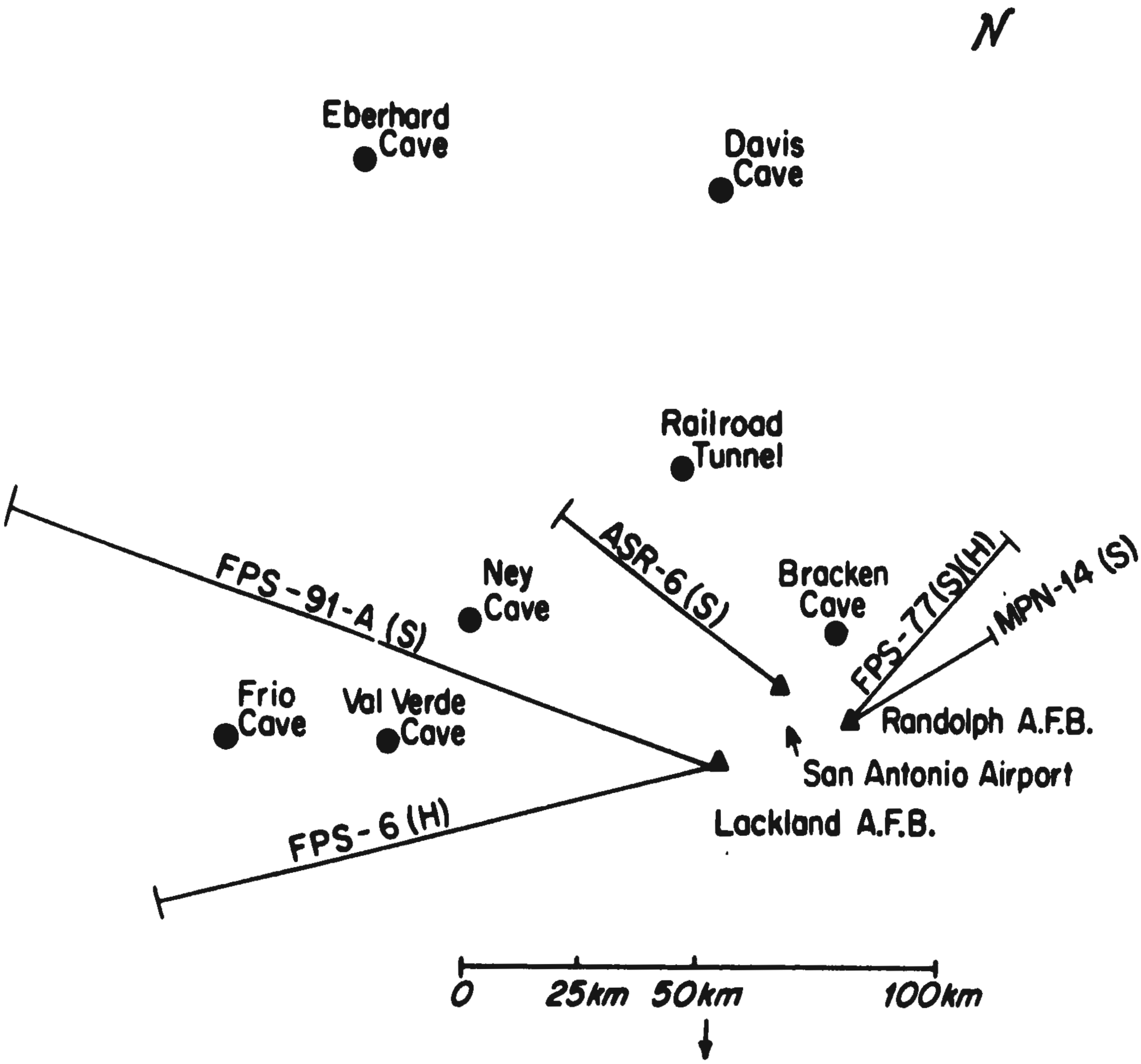


Figure 5. The triangles on the above figure show the locations of the radar installations in the San Antonio, Texas, area which we used to observe bat flights. The lengths of the lines extending from the triangles indicate the approximate maximum ranges at which each radar could detect bats. The letters and numbers along each line identify the radars at each site (see text). The letter (H) indicates that a radar was used in the height-finding mode and the letter (S) indicates that a radar was used in the search mode. The circles show the location of several large caves, each housing an estimated million bats or more.

radar at San Antonio Airport provided the most detailed information on the horizontal distribution of bat flights near the Bracken cave, and the FPS-77 weather radar at Randolph AFB provided the most detailed data on their vertical distribution. Consequently, the majority of our observations from 1967 through 1972 were made on these radars. Unfortunately, in 1974 we were able to use the ASR-6 for only 10 days. The MPN-14 provided more detailed information on the horizontal distribution of bat flights within 25 km of Randolph AFB than did the FPS-91-A, and so most of our 1974 search radar observations were made with the lower powered MPN-14. The MPN-14, however, provided far less detailed data on bat flight directions than did the other two search radars, and all information on flight directions presented in this report was obtained from the ASR-6 and FPS-91-A.

Observations were made from 20 to 29 October 1967; 6 June to 11 August 1968; 19 July to 26 August 1971; 17 June to 17 August 1972; and 3 June to 18 August 1974. From 1967 through 1972, the majority of our observations were made in the evening to coincide with pilot training operations. In 1974, morning observations were also made whenever possible. All radars were used on a noninterference, time-available basis. Other operations at the radar sites often prevented our obtaining information on bat activity. Whenever possible, we began making observations two hours before sunset or sunrise and continued for as long as we could detect bat activity on the radars.

Information was recorded from the Plan Position Indicator displays (PPI) of the search radars with a Polaroid 180 camera, a 35 mm still camera, or with a time-lapse 8 mm camera which recorded an entire evening's or morning's activity. Samples of such photographs are shown in figures 6 and 8 thru 10. The radars were operated with linear polarization and minimal Sensitivity Time Control (STC) to maximize small targets. On some days, Moving Target Indicator (MTI) was used to reduce ground return. Circular Polarization (CP) was occasionally used to reduce the returns from rain clouds. For information on how these "anticlutter" circuits affect the sensitivity of a radar to flying wildlife see reference 13.

Data on the altitude of bat flights were recorded from the Range Height Indicators (RHI) of the weather and height-finding radars with a Polaroid camera (Figs. 7-10) or by visual inspection of the display when the camera was not available. No anticlutter circuits were used on the height-finding radars. The Stepped Attenuation circuit (SAT) of the FPS-77 weather radar was used to obtain estimates of the density of bat flights. For a discussion of the use of the SAT in estimating the density of flying wildlife see reference 14. Specific instructions for tuning the ASR-6 and MPN-14 search radars and the FPS-77 weather radar to detect bat targets are given in Appendix A.

OBSERVATIONS FROM A HELICOPTER

Williams and Williams (Refs. 3, 4) made visual observations from a helicopter to verify the presence of bats within the targets seen on radar. For this purpose, they used a small twin rotor fire rescue helicopter equipped with floodlights. Bats could be reliably identified if they passed through a cylindrical area roughly 30 m long and 15 m in diameter, extending downward from the aircraft at about 45^{o}. Such observations were possible only if the airspeed of the helicopter was kept below 60 km/hr. It was not possible to reliably count more than 30 animals per min passing through the searchlight.

WEATHER OBSERVATIONS

Hourly surface weather observations were obtained from the 24th Weather Squadron at Randolph AFB. No direct measurements of winds aloft are made in the San Antonio area. We obtained estimates of winds aloft twice daily, at 00:00 and 12:00 GMT, by comparing data obtained by radiosondes at Victoria, Midland, and Brownsville, Texas. Local weather bureau personnel informed us that this technique should give winds aloft to within 20°, for windspeeds greater than 10 km/hr. On two evenings we were able to verify this accuracy by tracking helium balloons with a small, mobile search radar.

EXPERIMENTS WITH STROBE LIGHTS

One possible solution to the bat problem, of course, is to discover methods of clearing bats from runway areas and/or causing them to avoid aircraft. We have investigated the effectiveness of several sensory stimuli in producing avoidance reactions in Mexican free-tailed bats.

Experiments described by Williams and Williams (Ref. 3) indicated that caged bats were disturbed by the sounds emitted by nearby T-38 aircraft. The level of sound produced by a T-38 in flight, however, is obviously not sufficient to prevent bat strikes, and an increase in the overall level of sound produced by the T-38 would have an adverse effect on both pilots and civilians in the vicinity of Randolph AFB. A selective increase in sound frequencies audible to bats but not humans (30 to 150 kHz) would probably accomplish little due to the rapid atmospheric attenuation of these frequencies. In other tests, ultrasonic whistles of various frequencies, sirens, compressed air powered fog horns, and small explosive charges were found to be largely ineffective in altering the flight directions of bats leaving the vicinity of the Bracken cave. On the basis of these experiments, we feel that the development of an effective auditory bat deterrent is not likely in the near future.

A preliminary study with high powered strobe lights, conducted at Randolph AFB during the summer of 1972, indicated that such lights might prove to be a practical deterrent. Folklore to the contrary, certain species of bats can see well and some species use vision for orientation (Refs. 15, 16). Unfortunately, the study had to be terminated after only two evenings due to the possibility of the strobe lights causing visual damage to base personnel.

A more comprehensive study of the bat deterrent properties of strobe lights was performed during the summer of 1974. The strobe used in the study, a Tripplite model ST-1, had an output of approximately 1,000,000 international candles, could produce from 60 to 1000 flashes per min, and was modified to emit a vertical, cone shaped beam subtending approximately 110°. The presence or absence of bats was determined by means of two Holgate Ultrasonic Receivers and Microphones, which are capable of detecting and amplifying the high frequency sounds emitted by bats and converting them to frequencies audible to man. The audio output of each receiver was converted to a DC signal and fed into a 100 microampere Rustrack strip chart recorder. A signal from the receiver produced a deflection of the recorder stylus away from the baseline of the strip chart. The stylus produced a dot on the chart every two sec, recording the strength of the signal. The chart moved at a speed of 30.48 cm/hr. Tests in a flood-lit area at night showed that these bat detection systems could record the presence of a bat up to 30 m away flying through a cone shaped area subtending roughly plus or minus 40° from the principal axis of the microphone. The receivers indicated that the most intense sounds emitted by Mexican free-tailed bats were in a range of from 40 to 60 kHz. During our tests, the receivers were adjusted to detect sounds of 50 kHz. The sensitivities of the two detection systems were matched as closely as possible.

The tests were carried out at two locations along the Cibolo Creek, approximately 10 km NW of Randolph AFB, where large numbers of Mexican free-tailed bats appeared each evening to drink and to forage for insects. Four hours before sunset, one of the bat detection systems and the strobe light were placed at one of the locations and turned on. The principal axis of the microphone was aligned as closely as possible with the principal axis of the strobe light. The other bat detection system was set up at the second location, approximately 300 m away. Three experiments were performed, each lasting a total of six days. In the first experiment, the light was set to pulse at a frequency of 60/min, in the second at 300/min, and in the third at 1000/min. In each experiment, the position of the strobe light was alternated between the two locations on successive evenings. The equipment was retrieved each evening 3 hours after sunset.

SECTION III

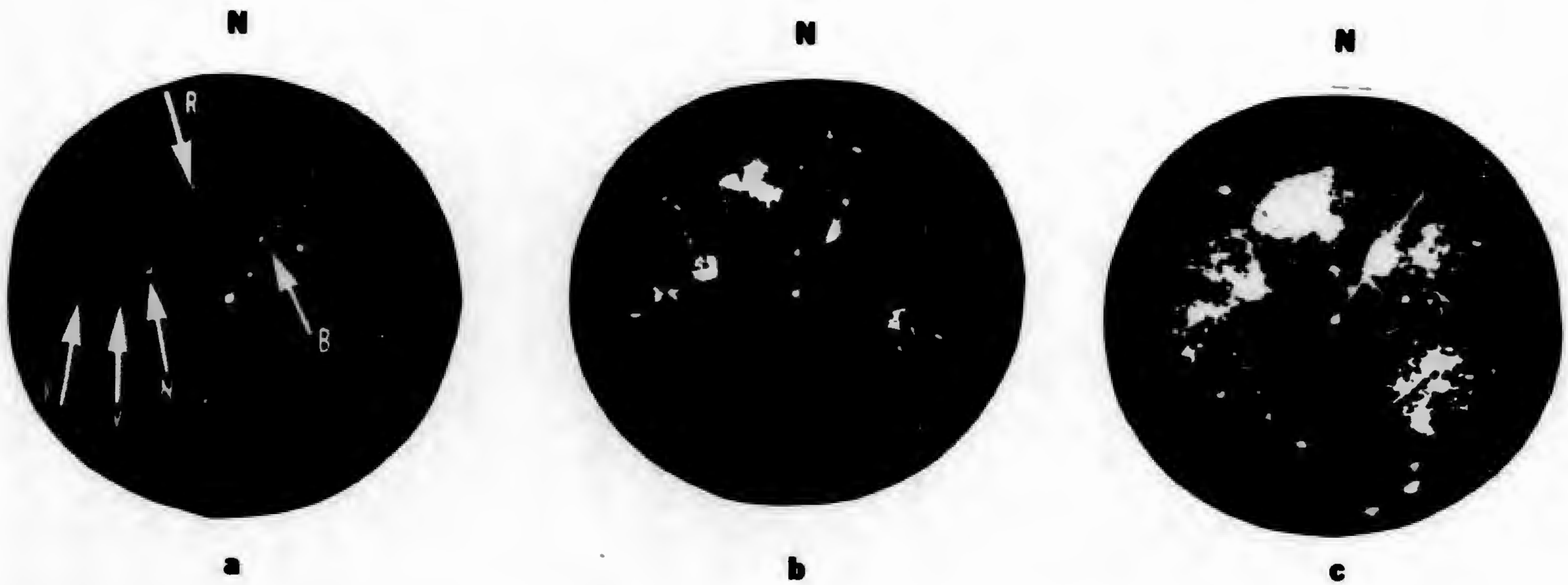
OBSERVATIONS AND RESULTS

APPEARANCE AND DEVELOPMENT OF BAT RADAR TARGETS

Radar observations were made on 226 occasions, and approximately 4 hours of radar data were collected during each observation period. One hundred and fifty-four observation periods were conducted during the evening and 72 in the morning. Simultaneous data from both search and height-finding radars were obtained on 99 evenings and 52 mornings, exclusively from search radars on 30 evenings and eight mornings, and from height-finders alone on 15 evenings and eight mornings. Bat targets were not observed on 10 evenings and four mornings because of rainstorms in the area which made it impossible to detect bat targets on the radar displays.

Figure 6 shows a series of photographs of the Lackland AFB search radar PPI and illustrates the horizontal development of radar echoes which represent the emergence of bats from several large caves. The white arrows in figure 6a indicate the position of five large bat roosts, including the Bracken cave. This photograph was taken 20 min after sunset. At this time, observers at the Bracken cave reported that a column of bats had emerged from the cave and attained an altitude of at least 150 m; the column was approximately 1.5 km long.

Both circumstantial and direct evidence indicated that these large radar echoes were due to bats. These echoes are seen only during months when large numbers of Mexican free-tailed bats are present in the area, only near sunrise and sunset, and reliably only near large active bat roosts. The presence of bats in these large radar targets was confirmed by visual observations from a helicopter (see below).



<u>Figure 6</u>. Plan Position Indicator photograph of bats emerging from several caves near San Antonio, Texas, on August 10, 1968. Photographs are of the Lackland AFB FPS-91-A search radar PPI with MTI. The photographs were taken, (a) 20 minutes after sunset, (b) 40 minutes after sunset, (c) about 1 hour after sunset. The white ring at about 1/4 radius of photograph (c) is 32 kilometers range from the radar site. The white arrows in photograph (a) indicate the location of several known bat roosts: Firo cave (F), Val Verde cave (V), Nye cave (N) and the Bracken cave (B), and a deserted railroad tunnel (R). Note that large radar echoes in photographs (b) and (c) appear near these known roosts.

Figure 6b shows the appearance of the same radar display 20 min later. All bat echoes have expanded. In some cases, a bat echo expanded relatively rapidly in only one direction. In other cases, the echoes expanded in two separate directions, presumably indicating two flight directions. At the same time figure 6b was taken, observers at the Bracken cave reported that the column of bats extended as far (more than 1.5 km) and as high (about 300 m) as they could see in the dim light. Also, in figure 6b, numerous small echoes may be seen developing to the southeast of the radar. These followed the same pattern of development as the larger ones, remaining essentially stationary and slowly expanding, probably indicating the location of a large number of relatively small bat roosts.

The bat echoes continued to expand until they reached the size indicated in figure 6c, about one hour after sunset. They then gradually grew more diffuse until it appeared that a fine clutter covered almost the entire PPI display. This diffuse activity often remained visible for several hours.

Repeated visual inspection of the PPI and time-lapse movie films showed that the large echoes were made up of many smaller targets. These small targets appeared near the location of the bat roost, then moved outward through the length of the large echo, and diminished and disappeared at its periphery. Due to the large number of these small targets, it was not possible to measure their exact speed. In all cases, however, the majority of small targets moved toward the area or areas in which the large echo was expanding most rapidly. We termed such areas the leading edges of the bat echo.

Figure 7 shows two photographs of the RHI display of the FPS-77 weather radar used in the height-finding mode with the radar beam directed toward the Bracken cave. These photographs serve to illustrate the typical vertical distribution of bat echoes. Bats emerging from the cave were first seen at sunset (Fig. 7a) as a small mound rising above the clutter caused by ground return.

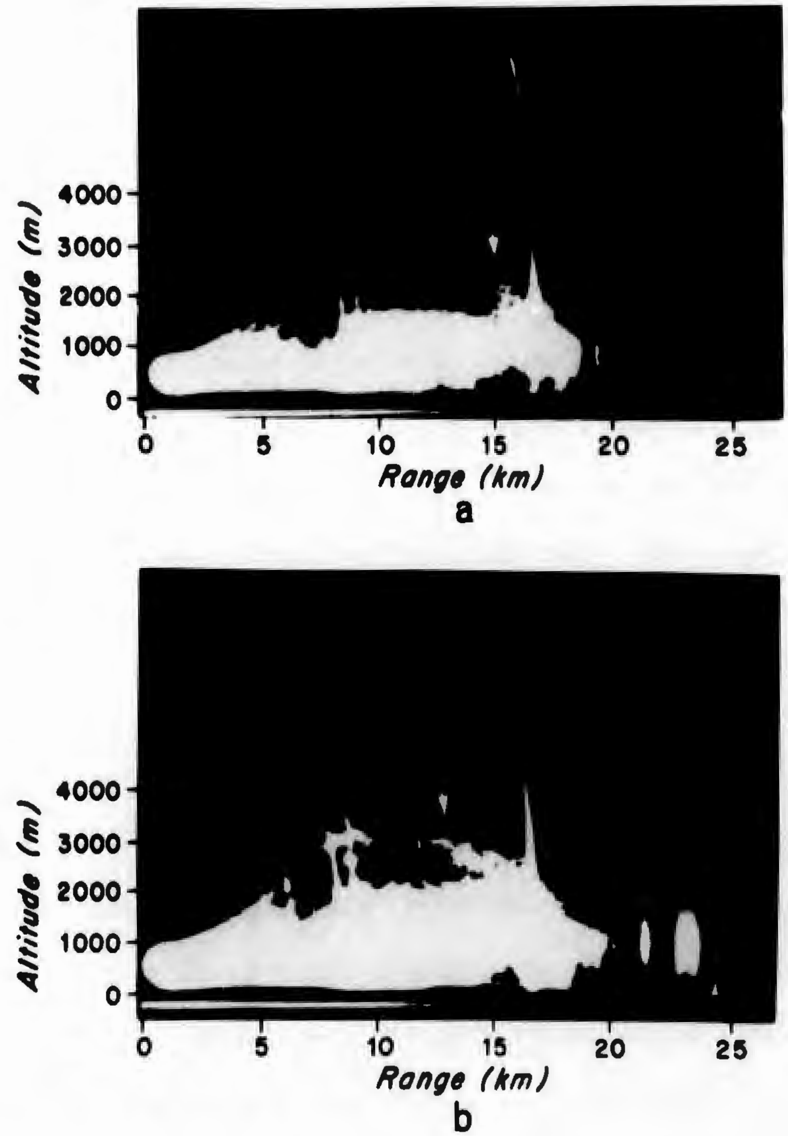


Figure 7. Altitudinal distribution of bats emerging from Bracken cave on June 27, 1969. Photographs of the RHI display of the FPS-77 weather radar at Randolph AFB, Texas, (a) taken at sunset shows the pattern of ground return. The bat flight may be seen as a small mound rising toward the tip of the white arrow. The two vertical white lines are range marks. (b) taken approx. 20 min later illustrates the development of a layer of bats (white arrow) leaving the cave.

In figure 7b, taken 20 min later, the column has risen to a height of approximately 3,000 m and has progressed about 9 km toward the radar. The increased return near the ground in figure 7b probably represents low flying bats. See reference 17 for a discussion of the potential advantages of high altitude flight to Mexican free-tailed bats.

In the morning, when the bats returned to the cave, the sequence of events shown in figures 6 and 7 occurred in reverse order. Approximately an hour before sunrise, small echoes would appear in the vicinity of the bat roosts. These would increase in number until they formed large radar echoes similar to those in figure 6b. Over the next few hours these echoes would slowly diminish in size, disappearing usually about 1 hour after sunrise.

HELICOPTER OBSERVATIONS

The presence of large numbers of bats within these radar targets was confirmed by visual observations from a helicopter. On two evenings, the aircraft was directed to fly across the large radar echo near the Bracken cave. Within the radar target, large numbers of bats would pass through the light beam more rapidly than an observer could count (more than 30 per min) and then disappear, followed rapidly by another group. Beyond the perimeter of the radar targets, bats were far less numerous and were flying singly or in groups of less than 10. The greatest concentration of animals outside the radar echo was usually within 160 m of the ground. These bats were often observed flying with the characteristic darting flight of feeding animals. Behavior typical of feeding was not observed for bats flying at altitudes of over 200 m.

Further data on the flight patterns of bats leaving the Bracken cave were obtained by observing the bat flight from the helicopter before sunset. The aircraft was positioned about 1 km west of the column of emerging bats, at an altitude of about 330 m. The thick column of bats which emerged from the cave first broke up into large groups of 10,000 to 1,000 animals; these groups in turn divided into groups of 1,000 to 100. These small groups may well have formed the small targets seen to move across the large bat echoes on the search radar PPI displays. Presumably, these small groups continued to disperse until, near the edge of the large radar echoes, they diminished below the critical density for detection by radar.

It thus appears that the small targets seen on radar were due to the reflection of radar energy from groups of more than 100 animals flying close together. The existence of such concentrations of small animals explains the ability of radar to detect bats at ranges of over 150 km.

VARIATIONS IN BAT RADAR ECHOES

Major changes in the distribution of bats from year to year were noted on the Lackland AFB search radar. During the summer of 1971, several caves formerly occupied by millions of bats appeared to be essentially deserted. The populations of several other roosts, including the Bracken cave, appeared to have increased. Further changes in population density were noted during the summers of 1972 and 1974. The overall pattern of airborne hazards in the San Antonio area, therefore, changed considerably between years. The factors which elicit these shifts in population density are unknown, but the choice of roosts appears to be made in the early spring when the bats arrive in Texas from their Mexican winter roosts. The population density of a roost appears to remain relatively stable during a given summer.

Bat echoes near the Bracken cave varied in the times of their appearance on and disappearance from the radar displays. Bat echoes also differed in maximum size, altitudes, primary directions of motion and speeds of expansion. On some evenings, the bats left the cave in a single, continuous flight. On other occasions, the bats stopped emerging from the cave from one to four times, for periods of from 10 to 40 min. The morning flight to the cave area always appeared to be uninterrupted.

The time of appearance of evening flights on the radar displays varied from 113 min before sunset to 31 min after sunset. The bats appeared on the radar displays from 7 to 12 min after leaving the cave. The average time of appearance was 64 min before sunset (SD = 41, N = 144). The bats remained visible on the display until from 18 to 207 min after sunset (X = 98, SD = 56, N = 144). Morning flights were detected from 86 to 12 min before sunrise (X = 58, SD = 19, N = 68), and remained visible on the displays until from 17 to 131 min after sunrise (X = 41, SD = 23, N = 68).

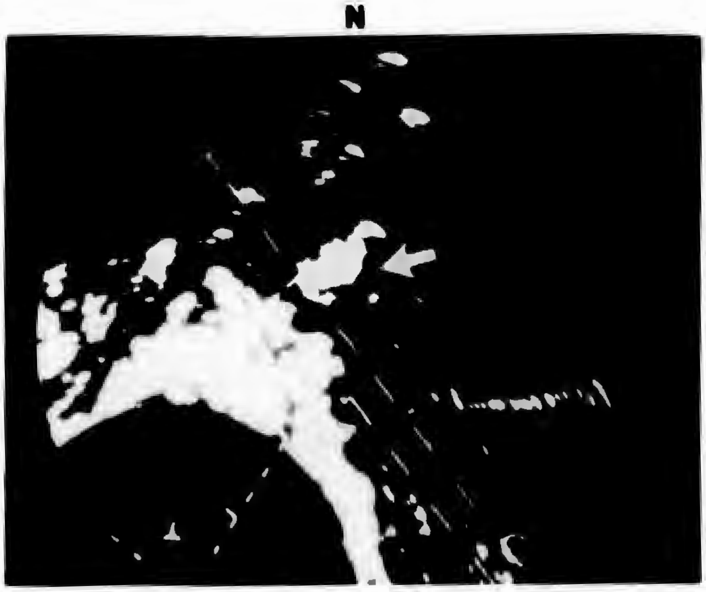
The maximum areas covered by bat echoes during evening flights from the Bracken cave ranged from 25 to over 500 km^2 (X = 240, SD = 105, N = 129); those covered by morning flights varied from 18 to 370 km^2 (X = 195, SD = 88, N = 60).

The maximum altitudes recorded for evening flights ranged from 300 to 3,100 m (X = 1,350, SD = 600, N = 114). Three hundred meters was the approximate minimum altitude at which bat flights could be detected due to "ground clutter" on the RHI display. The maximum altitudes recorded for morning flights ranged from 300 to 2,200 m (X = 650, SD = 275, N = 60).

Three dimensional drawings were constructed for each of the 99 evenings and 52 mornings for which simultaneous search and height-finding radar data were available. Examples of these drawings are shown in figures 8g, 9g, and 10g. Inspection of the drawings revealed that both evening and morning bat flights could be grouped into three classes. Type I bat flights (illustrated in Fig. 8) had maximum altitudes of from 800 to 2,800 m. Height-finding radar indicated little variation in the density of bats between the upper limit of the ground clutter and the bats' maximum altitude. In Type II flights (shown in Fig. 9), the bats reached maximum altitudes of from 1,500 to 3,100 m. In this type of flight pattern, the bats appeared to form a "cloud" which was clearly separated from the ground. Observations of Type II flights repeatedly indicated that the bats were distributed as a layer approximately 350 to 600 m thick. In Type III flights (illustrated in Fig. 10), the bats reached maximum altitudes of 400 to 1,300 m and then rapidly descended to altitudes of less than 500 m. After a short time, they were no longer visible on either the ASR-6 or MPN-14 search radars and could be detected on the FPS-77 weather radar only because they "filled in" normally clear areas in the ground clutter.

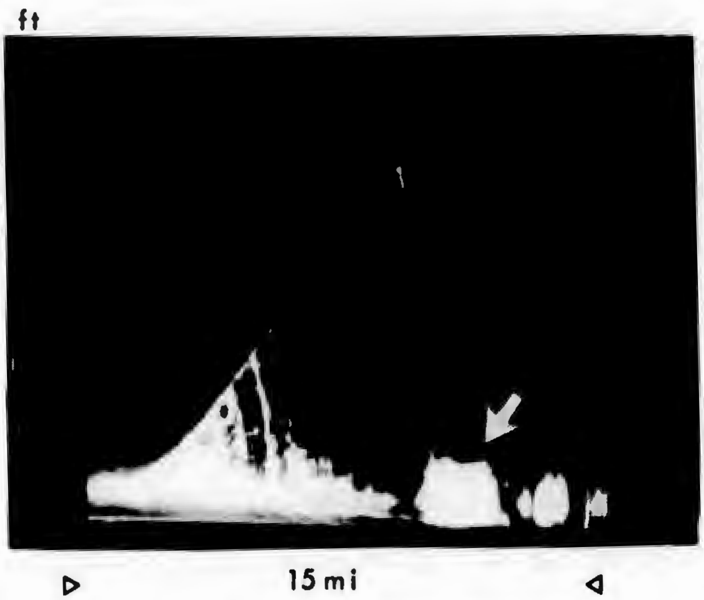
All three types of evening bat flights appeared to involve three separate phases of activity. Examples of each phase of activity for each type of bat flight are shown in figures 8, 9, and 10. Phase I activity involved the emergence of the bats from the cave and ascent to the flight altitudes selected for the evening. This phase was characterized by an ascending formation with a relatively small horizontal distribution, located within a few km of the roost. The position of the bat flight in Phase I was relatively stable from night to night. It was usually possible to identify one or two primary directions of motion for this phase. Bat flights in Phase II were still ascending with bats near the leading edge or edges of the echo changing to level flight and moving away from the area of the cave. On 72 of the 79 evenings we were able to obtain precise information on flight directions, the bats moved toward the NW or NE during both Phase I and Phase II. In 41 of these cases, the bats moved toward both the NW and NE. The leading edge or edges of bat echoes in Phase I moved at speeds ranging from 8 to 24 km/hr ($X = 18$, $SD = 3$). Those in Phase II varied from 10 to 121 km/hr ($X = 70$, $SD = 22$).

In Phase III, the bat flight usually changed direction, moved away from the area of the cave, and finally dispersed. In Phase III, the leading edge of the echo moved in a direction between SSW and SE on 75 evenings, taking the



a

Type I, Phase I, activity on the PPI, 38 min before sunset. The white arrow indicates the position of the bat echo. The circular range marks are 8 km apart. The circle at the lower right of the picture shows the location of Randolph AFB. The parallel, dotted lines show the runway approaches.



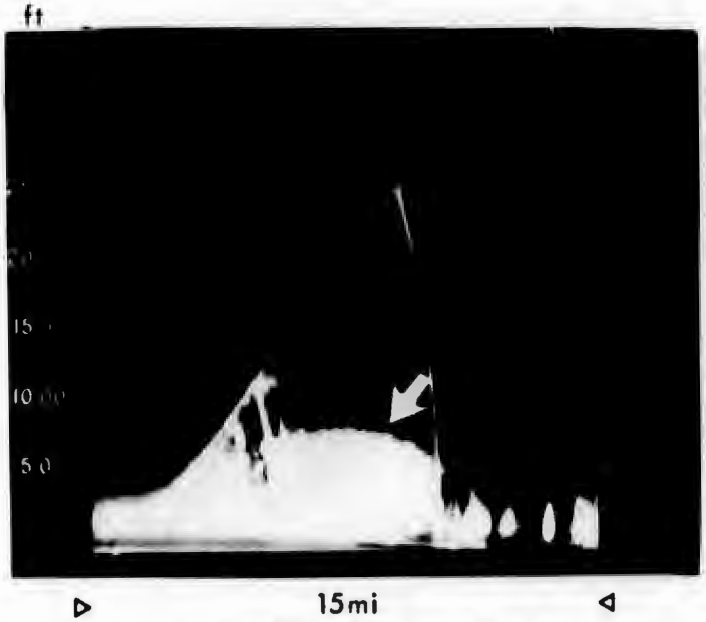
b

Type I, Phase I, activity on the RHI, 35 min before sunset. The white arrow indicates the position of the bat echo. The three vertical white lines are range marks, 8 km apart. The radar is directed toward 330° azimuth.

Figure 8. PPI (ASR-6) and RHI (FPS-77) photographs and a drawing illustrating a typical Type I evening bat flight. Photographs are of bats emerging from the Bracken cave on July 23, 1972.

c

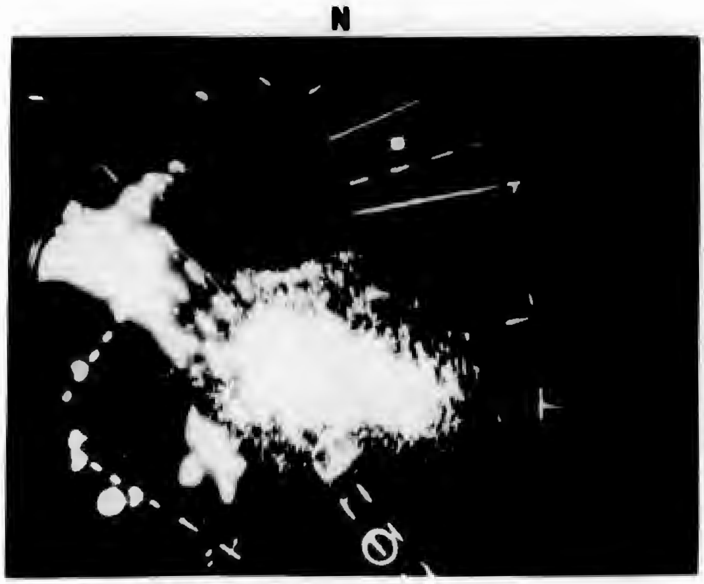
Type I, Phase II, activity on the PPI, 8 min after sunset. The upper arrow shows the position of the bat echo. The lower arrow shows the normal T-38 traffic patterns.



d

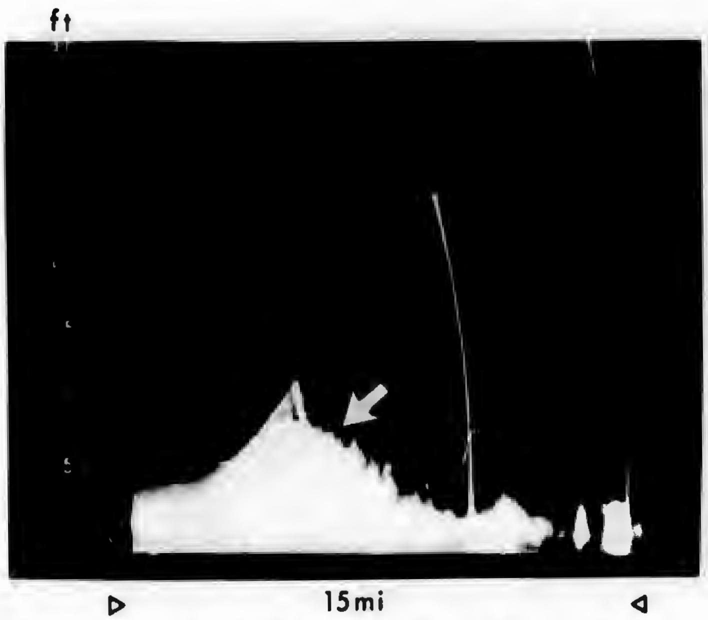
Type I, Phase II, activity on the RHI, 12 min after sunset. The arrow indicates the position of the bat echo. The radar is directed toward 355^{o} azimuth.

Figure 8. (Cont'd)



e

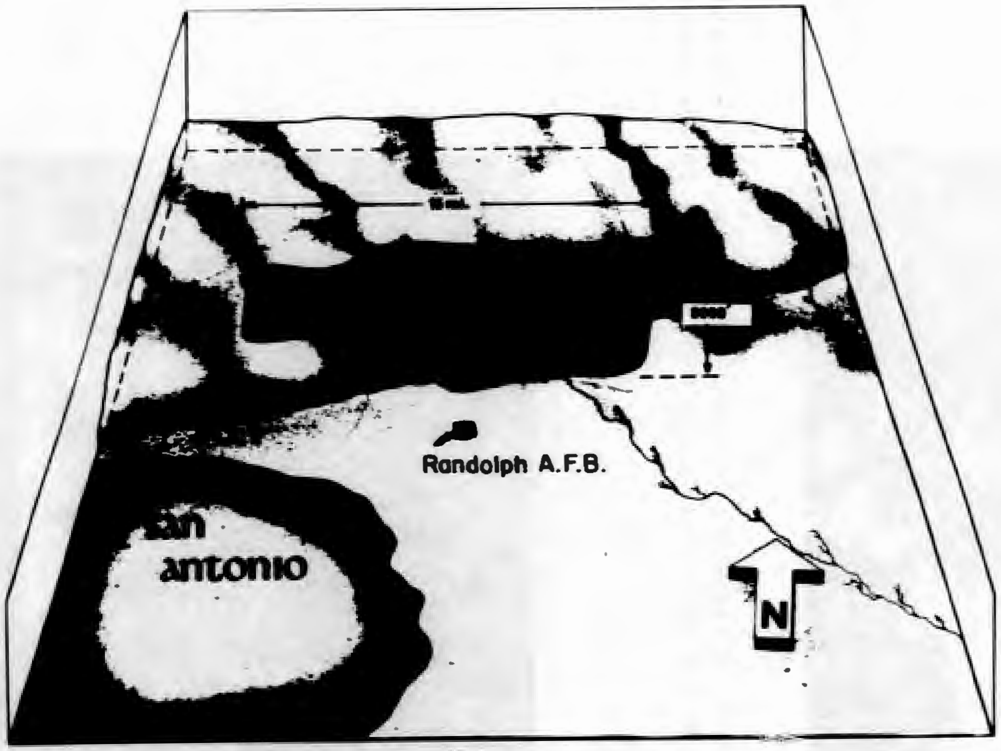
Type I, Phase III, activity on the PPI, 84 min after sunset.



f

Type I, Phase III, activity on the RHI, 86 min after sunset. The radar is directed toward 355° azimuth.

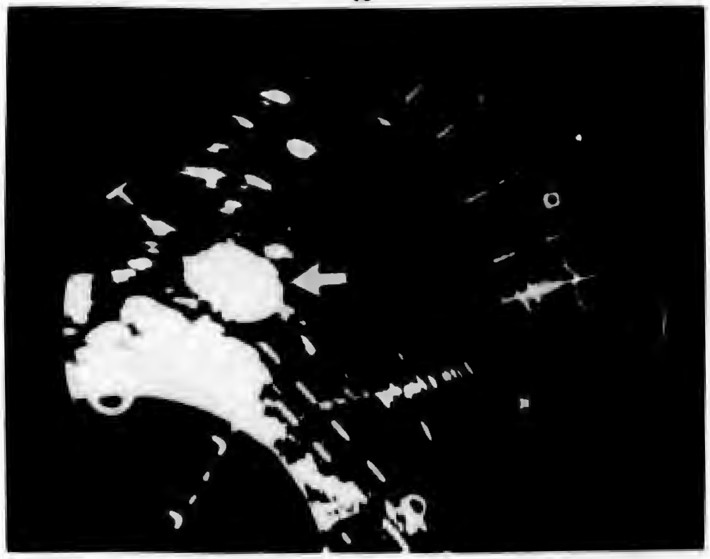
<u>Figure 8</u>. (Cont'd)



A three dimensional reconstruction of a Type I, Phase II, bat emergence from the Bracken cave. The density of the bat flight is approximately equal from its maximum altitude to ground level.

<u>Figure 8</u>. (Cont'd)

N



a

Type II, Phase I, activity on the PPI, 18 min before sunset. The white arrow shows the location of the bat echo. Refer to figure 8 for an explanation of the video map.

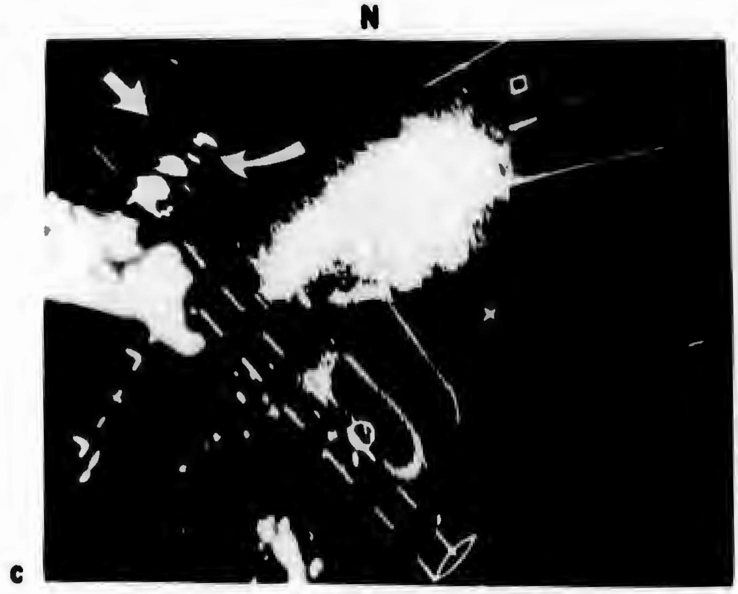
ft

b

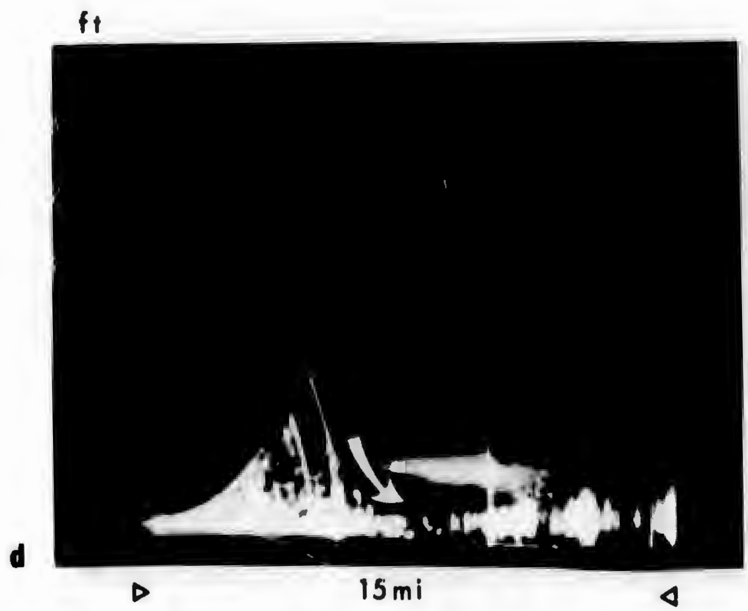
▷ 15mi ◁

Type II, Phase I, activity on the RHI, 20 min before sunset. The white arrow shows the location of the bat echo. The radar is directed toward 326° azimuth.

Figure 9. PPI (ASR-6) and RHI (FPS-77) photographs and a drawing illustrating a typical Type II evening bat flight. Photographs are of bats emerging from the Bracken cave on July 10, 1972.

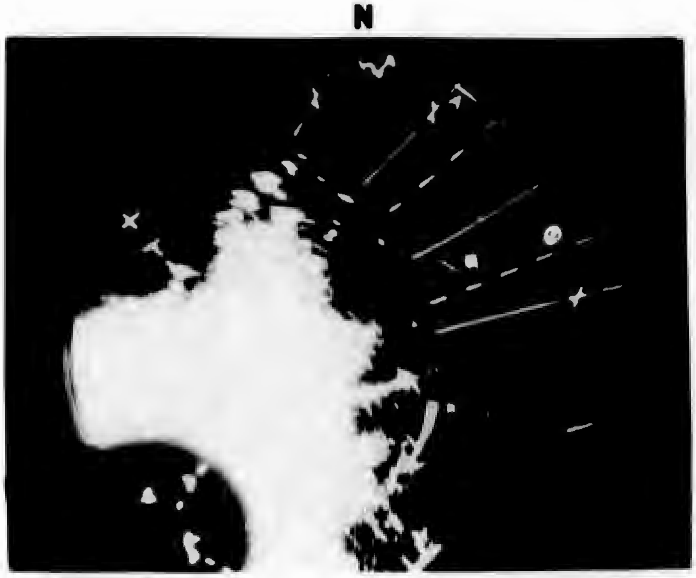


Type II, Phase II, activity on the PPI, 45 min after sunset. The upper white arrow indicates the flight path of a T-38 on a straight-in approach. The lower white arrow shows the approximate location of the Bracken cave.



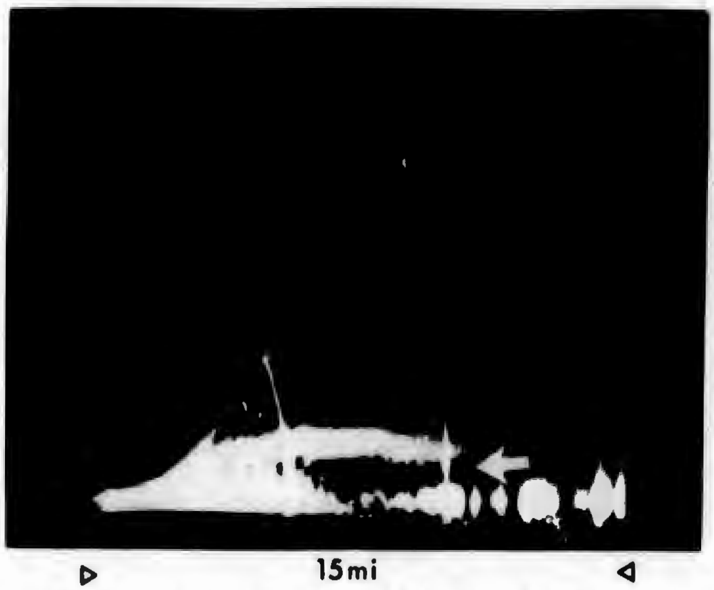
Type II, Phase II, activity on the RHI, 50 min after sunset. Note the separation of the bat echo from the ground indicated by the white arrow. The radar is directed toward 359^{o} azimuth.

Figure 9. (Cont'd)



e

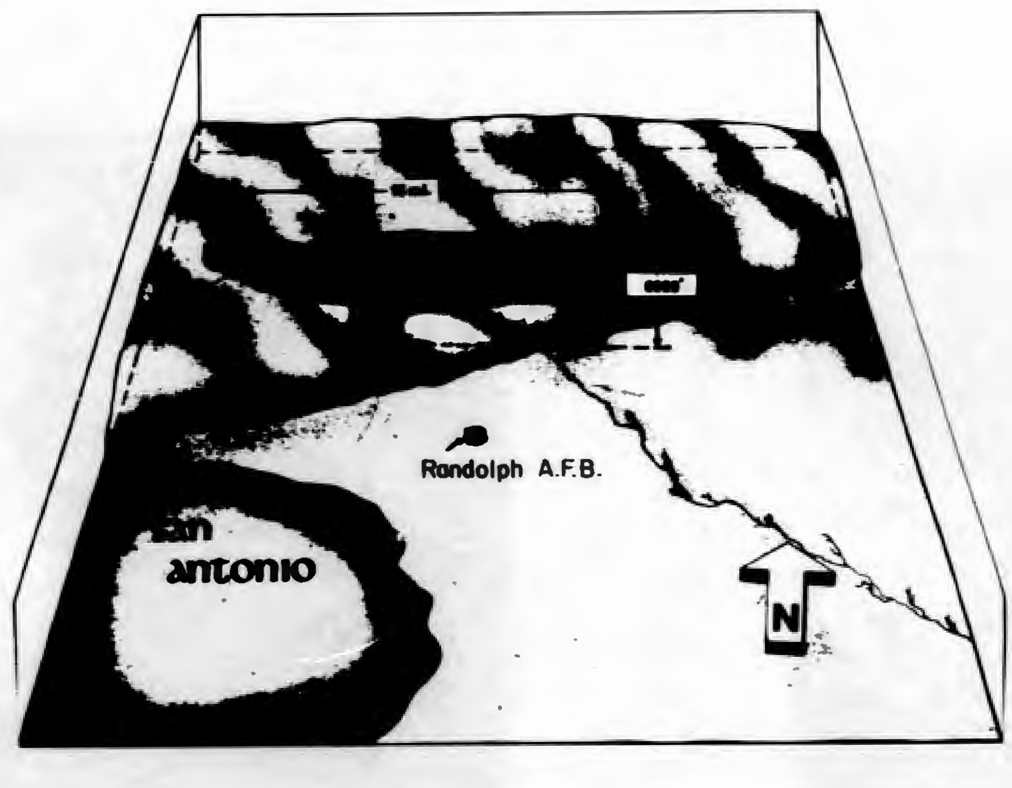
Type II, Phase III, activity on the PPI, 120 min after sunset. The white arrow shows the location of Randolph AFB.



f

Type II, Phase III, activity on the RHI, 110 min after sunset. As shown by the white arrow, the bat echo is clearly separated from the ground. The radar is directed toward 355^{o} azimuth.

<u>Figure 9</u>. (Cont'd)



A three dimensional reconstruction of a Type II, Phase II, bat emergence from the Bracken cave. Note the anvil-like shape of the bat flight and the fact that, for the most part, the flight is separated from the ground.

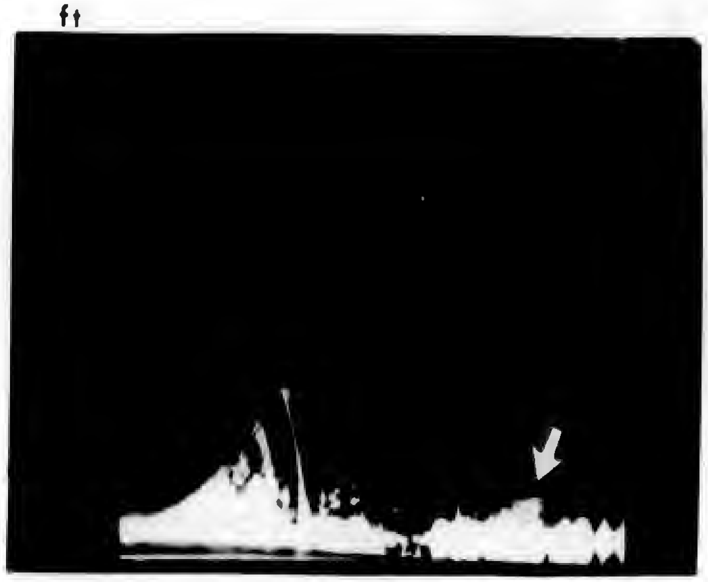
Figure 9. (Cont'd)

N

a

Type III, Phase I, activity on the PPI, 32 min before sunset. The white arrow shows the location of the bat echo.

ft



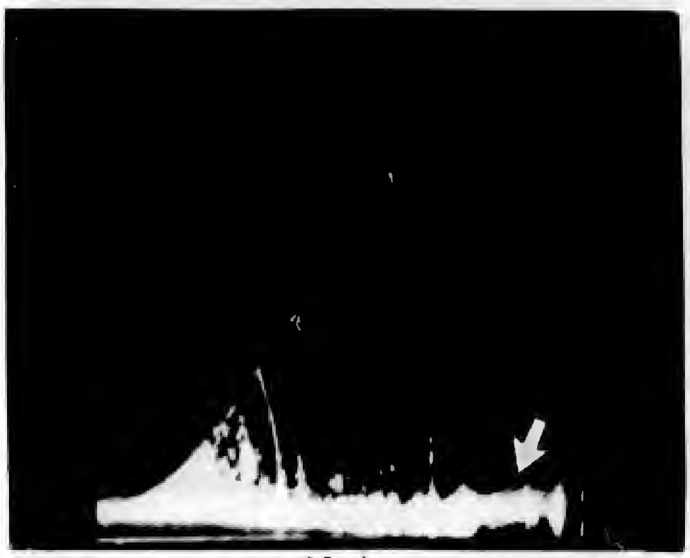
b

▷ 15 mi ◁

Type III, Phase I, activity on the RHI, 30 min before sunset. The white arrow indicates the location of the bat echo. The radar is directed toward 329° azimuth.

Figure 10. PPI (ASR-6) and RHI (FPS-77) photographs and a drawing illustrating a typical Type III evening bat flight. Photographs are of bats emerging from the Bracken cave on June 29, 1972.

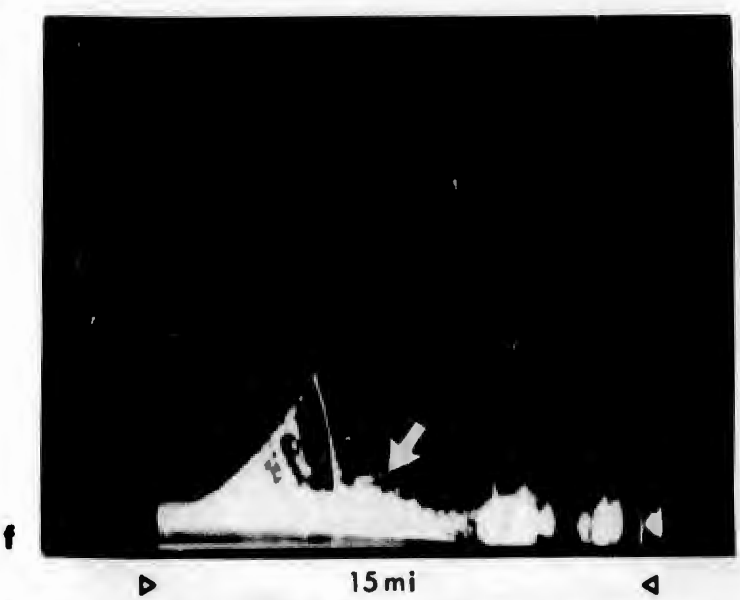
Type III, Phase II, activity on the PPI, 5 min after sunset. The white arrow shows the location of the bat echo.



Type III, Phase II, activity on the RHI, 2 min after sunset. The white arrow shows the location of the bat echo. The radar is directed toward 335° azimuth.

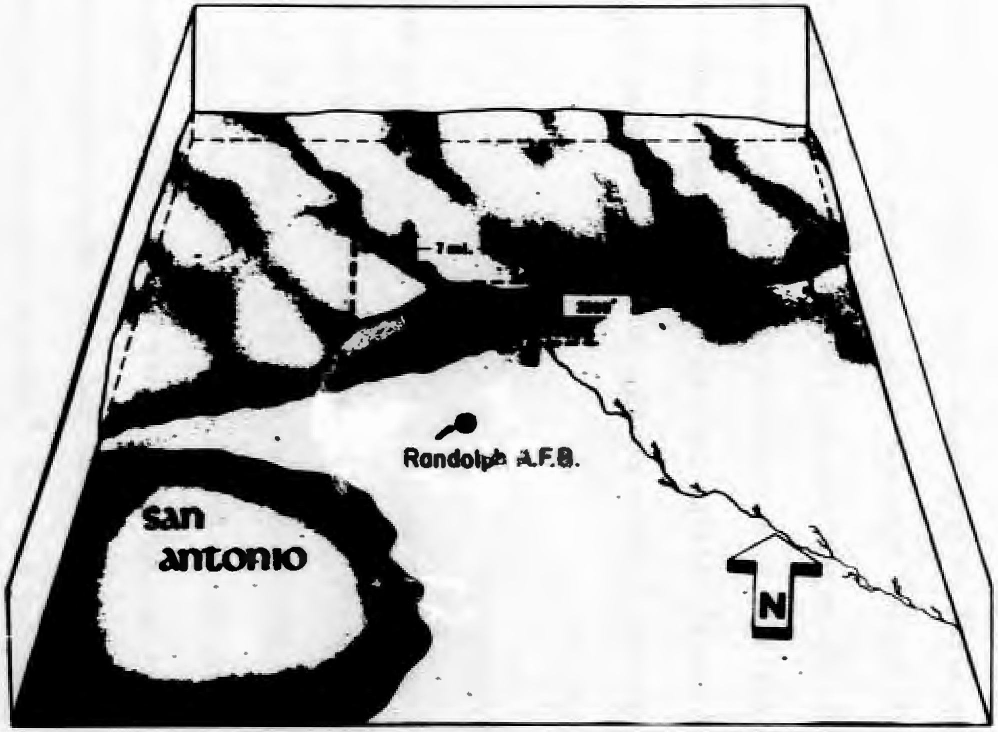
Figure 10. (Cont'd)

Type III, Phase III, activity on the PPI, 45 min after sunset. The white arrow shows the position of a few small bat targets. Other small targets are visible to the NW of these targets.



Type III, Phase III, activity on the RHI, 55 min after sunset. The white arrow shows the position of several small bat targets. The majority of the bats are obscured by ground return. The radar is directed toward 332° azimuth.

Figure 10. (Cont'd)



g

A three dimensional reconstruction of a Type III, Phase II, bat emergence from the Bracken cave. Such low altitude flights appear to pose a major hazard to T-38 aircraft.

<u>Figure 10</u>. (Cont'd)

bats toward and over Randolph AFB. Although we were unable to determine flight directions with any degree of accuracy with the MPN-14 search radar, large numbers of bats were detected approaching and flying over the base on 47 of the 50 evenings in 1974 on which we made observations with this unit. The speed of the leading edge of Phase III echoes ranged from 7 to 54 km/hr ($\bar{X}$ = 18, SD = 12).

Morning bat flights appeared to involve only two phases of activity, return to the cave area and descent into the cave. We were able to obtain precise directional information on morning bat flights on only 18 days. On all of these days, the majority of bats detected approached the cave area from directions between SW and SE, flying directly over Randolph AFB. Morning observations with the MPN-14 search radar during 1974 always showed large numbers of bats passing over the base.

RESULTS OF STROBE LIGHT EXPERIMENTS

Large numbers of bats were recorded by the detection systems on each night of testing. Bats were always first detected during the hour before sunset. Therefore, only data collected from 1 hour before sunset to 3 hours after sunset each evening were considered in our statistical analyses. The level of bat activity recorded on each strip chart was scored by connecting the dots on the chart produced by the stylus and then calculating the area between this line and the baseline for each 5 minute interval on the chart. A separate t-test for matched samples (Ref. 18) was performed on the data from each of the three experiments in order to determine if there was a significant difference between the levels of bat activity recorded in the strobe-lit and dark conditions. The results of all three experiments indicated that there was no significant difference between the two conditions: 60 pulse/min experiment ($t = 0.90$, $df = 287$, $p > 0.20$), 300 pulse/min experiment ($t = 0.74$, df = 287, $p > 0.20$), 1000 pulse/min experiment ($t = 0.81$, df = 287, $p > 0.20$). These results indicate that the strobe light used in these tests had no deterrent effect on bats foraging near the ground.

SECTION IV

THE BAT AVOIDANCE PROGRAM

BAT ACTIVITY AND PILOT TRAINING OPERATIONS

At Randolph AFB, daytime pilot training operations usually begin at sunrise and end approximately two hours before sunset. When scheduled, usually twice a week, nighttime training begins at sunset and continues for 2 to 3 hours. The prevailing winds at Randolph AFB are from the SE. On most days and nights, aircraft launch toward the SE and land from the NW. Figure 9c shows a T-38 on a typical straight-in approach. Note that this approach takes the aircraft near the Bracken cave. The T-38 traffic patterns are shown in figure 8c. When in the pattern, aircraft seldom exceed altitudes of 1,200 m.

The bats are a hazard to T-38 aircraft using straight-in approaches of 18 km or more whenever the bats are emerging from or returning to the Bracken cave, and it is a rare morning or evening bat flight which does not travel directly over Randolph AFB (see Section III). Relatively few T-38 engines have been lost during late afternoon or morning training operations (see Section V). This fact is understandable when one considers the timing of bat flights. Afternoon pilot training operations are usually concluded befoie the bats emerge from the cave. Morning bat flights are usually well to the N of the base before sunrise. Since aircraft launch toward the SE on most mornings, travel to the E toward practice flying areas, and do not return to land for approximately 1 hour, they usually do not encounter the bats.

Avoiding the bat flight during nighttime training operations is a major problem. It is a virtual certainty that the bat flight will travel over the base when nighttime training operations are in progress. Examination of figures 8 thru 10 shows that each type of evening bat flight, and each phase of each type, presents a different pattern of hazards to aircraft.

It should not be imagined that the large bat flights emerging from and returning to the Bracken cave constitute the sole hazard posed by bats to Randolph AFB T-38s. On virtually any night from April or May through October, large numbers of bats may be observed foraging for insects near hangar and runway lights, and drinking from swimming pools and the water traps on the golf course. These bats are not all Mexican free-tails; large numbers of *Myotis velifer* are present as well. We do not know of any practical bat deterrent procedure which is capable of clearing bats from runway areas. Alterations of the habitat appear to be the only methods likely to reduce the number of bats feeding over the base (see Section VI). Also, large numbers of bats often roost in buildings on Randolph AFB. During the summer of 1974, we located roosts in 22 different buildings. The roosts were usually located in spaces near eaves and cornices. The bats typically gained access to these areas through cracks in the roofing tiles. Several roosts contained over 1,000 animals. On numerous evenings we watched bats depart from these roosts and fly off at low altitudes across the T-38 runways. A procedure for driving bats from these small roosts is given in Section VI.

Williams and Williams (Refs. 3,4) have described in detail the behavior of bats feeding over and roosting on Randolph AFB, and the reader is referred to their reports for further information on these aspects of the bat problem.

BAT AVOIDANCE BY MEANS OF REAL TIME RADAR OBSERVATIONS

During the summer of 1968, late afternoon, evening, and morning T-38 approaches to Randolph AFB were altered to avoid the immediate area of the Bracken cave. In August of 1971, a bat avoidance program was initiated which was based on real time radar observations. The program has continued each year since that time. The program made use only of equipment available in the San Antonio area and required the close cooperation of scientists, USAF personnel, and the Federal Aviation Administration. A primary concern was to train USAF personnel in all necessary procedures. The details of the program are described below.

Each night that training operations were conducted, and each late afternoon and morning in 1974, the bat flight emerging from or returning to the Bracken cave was observed with either the ASR-6 or the MPN-14 search radar, and with the FPS-77 weather radar. When Phase I activity was first noted on the search radar, the radar operator informed both the T-38 Supervisor of Flying (SOF) and the operator of the weather radar of the position and size of the bat flight by telephone. The weather radar operator determined the maximum and minimum altitudes of the bat flight and reported this information to the SOF. The SOF used the information from both radars to obtain a composite picture of the vertical and horizontal distribution of the bat flight and determined what action, if any, was required. This procedure continued, at 10 to 15 min intervals, until bats were no longer visible on either radar.

If observations indicated that the distribution of bats was such that T-38 aircraft could safely leave and return to the base, they were simply vectored away from the bat flight. If the bats were observed to be entering the T-38 traffic patterns, if pilots reported seeing large numbers of bats passing through their landing lights, or if one or more aircraft struck bats, the SOF advised pilots to reduce their speed and return to base. Both pilots and Supervisors of Flying were initially skeptical of the bat avoidance program and our suggestions were often disregarded. Enthusiasm for the program developed after several bat strikes occurred following a "bat warning."

Early in the summer of 1972, we made progress toward identifying evenings when aircraft are most likely to collide with bats. On three evenings when bats damaged T-38 engines, the distribution of bats emerging from the Bracken cave appeared quite different from that seen on nights when strikes did not occur. On these three evenings, Phase III bat activity was observed to disappear from the PPI display of the search radar at a position approximately 12 km NW of the base. Examination of the RHI photographs taken on these evenings indicated that the bats had descended to low altitudes (< 500 m) and then moved toward Randolph AFB. It was these observations which prompted us to construct the three dimensional drawings of bat flights which led to the grouping of flight patterns into three types (see Section III). The bat flights on the nights cited above, of course, were Type III flights. Reexamination of our data from 1967, 1968, and 1971 revealed that radar data had been recorded on 21 evenings when flight training operations were conducted. On these evenings, a total of seven engines were damaged either by bats or unidentified flying animals. Five of these seven engines were damaged on evenings when the bats flew a Type III pattern. The other two engines were damaged when aircraft flew directly through Phase I, Type II, bat flights.

From early summer of 1972 on, we recommended that nighttime pilot training operations be terminated whenever Type III bat flights were detected on the radar displays. In practice, it proved possible to determine that the bats would move toward the base at low altitudes and to cancel the training mission from 10 to 30 min before the bats entered the T-38 traffic patterns. On several evenings, it was possible to recall all aircraft to base without bat strikes being reported. On several other evenings, the bats arrived near or over the base before all aircraft could be recalled and aircraft struck bats either to the north of the base or while landing.

In April of 1974, following two evenings on which five engines were damaged, permission was given to halt all takeoffs and to divert aircraft aloft to Kelly AFB whenever Type III activity was detected. Type III activity was observed and this procedure followed on four evenings during the summer and fall of 1974. A single engine was damaged on one of these evenings, presumably by a bat, during a landing at Kelly AFB. All other T-38 training operations during the 1974 "bat season" were conducted without damage from bats or unidentified flying animals.

The information cited above constitutes all of our data concerning the relationship between T-38 engine damage and bat flight patterns. On all other occasions that bats damaged T-38 engines, we were either not in the San Antonio area or were unable to obtain radar data. The apparent relationship between engine damage and Type III bat flight patterns should, therefore, be regarded as a hypothesis rather than a well documented correlation. The fact that the majority of bat strikes occur within 12 km of the base and at altitudes of 350 m or less lends support to this hypothesis. It is likely, however, that some unknown percentage of these collisions involve either bats feeding over runway areas or departing from small roosts in base buildings.

Fortunately, Type III flights occur relatively infrequently. On the 114 evenings we were able to record information on the altitudes of bat flights, Type I flights were observed on 56 evenings, Type II flights on 34, and Type III on 24.

On each occasion that observations were made with the FPS-77 weather radar, we obtained, or attempted to obtain, a relative measure of the density of the bat flight with the SAT circuit. It was, however, not possible to relate the frequency of engine damage to bat density. On the majority of evenings that we made observations and T-38s were damaged, the bat flight was almost totally obscured by ground clutter on the RHI display and we could not obtain accurate density measurements.

PREDICTING EVENINGS WHEN TYPE III FLIGHTS ARE LIKELY TO OCCUR

Halting nighttime flight training and diverting airborn aircraft to Kelly AFB whenever Type III bat flights are detected results in added costs to the Randolph AFB training mission. Significant savings would be realized if one could forecast evenings on which Type III flights are likely to occur and schedule training operations on other evenings. Multiple regression analyses may be used to search for "predictors" which can be used to make forecasts. A comprehensive description and discussion of multiple regression techniques is beyond the scope of this report. For an excellent review of these statistical procedures, see references 19, 20, and 21.

Multiple regression analysis is a method for studying the effects and the magnitude of the effects of more than one independent (predictor) variable on the value of a single dependent variable using principles of correlation and regression. In preparation for the analysis, the investigator records the value of the dependent variable (DV) on a number of occasions, as well as the values of a number of other known or forecastable independent variables (X) which he suspects might be good predictors. The analysis fits a linear additive equation to the various values of the independent variables, and each variable is assigned a constant (C) which indicates its relative predictive "weight". The analysis also provides a corrective constant (K). The constants chosen are those which maximize forecasting accuracy for the values of the independent variables and the dependent variable on which the analysis was performed. The equation may then be used to forecast the dependent variable. The formula for the predictive equation where there are N predictor variables is as follows:

$$DV = K + C_1 X_1 + C_2 X_2 + \cdot \cdot \cdot \cdot C_N X_N$$

The square of the multiple correlation coefficient (R^2), the percentage of the variance in the dependent variable accounted for by the relationships between the dependent variable and the independent variables, is an indication of the reliability of forecasts one may expect when using the equation.

When using multiple regression equations, one often finds that inclusion of only a few of the independent variables in the equation gives forecasts that are almost as accurate as those obtained by including all of them. Stepwise regression is a variation of multiple regression that is used to find the smallest number of independent variables that provide a forecasting accuracy approximately equal to that obtained using all the independent variables. The stepwise technique constructs an equation by adding one independent variable at a time. The single variable which is the best predictor is added on the first step. The second variable to be added is that which provides the best prediction in conjunction with the first step. Variables are added to the equation until the addition of further variables fails to significantly improve forecasting ability. The formula for making forecasts with the information provided by a stepwise regression analysis is the same as that for multiple regression analysis.

We performed a multiple regression analysis and two stepwise regression analyses with maximum altitude of bat flight, measured at a point 8 km NNW of Randolph AFB, the approximate northern edge of the T-38 traffic pattern, as the dependent variable. Low altitude flight (< 500 m) is, of course, characteristic of Type III flights. We selected 18 independent variables which we suspected might be good predictors of bat altitude. All of these variables are either known or may be forecast 24 hours in advance. In some cases, it was necessary to scale or transform independent variables in particular ways to meet the assumptions of the regression statistics (see Refs. 19-21). The scaling procedures for each of the predictor variables are described in Appendix B. The results of each of the regression analyses are shown in table 1. The sign of each assigned constant (C) provides useful information.

TABLE 1

MULTIPLE REGRESSION ANALYSES OF THE MAXIMUM ALTITUDE OF EVENING BAT FLIGHTS[1]

	Model Including All Predictors	First Stepwise Model	Second Stepwise Model
Predictor Variables (X)	Constant (C)	Constant (C)	Constant (C)
Date	- 0.0304 ns		
$Date^2$	+ 0.0032 ns		
Altitude - 24 hr	+ 0.5931 ***	+ 0.6236 ***	+ 0.6806 ***
Emergence - 24 hr	+ 0.0038 ns		
Temperature	+ 0.0917 **		
Temperature Trend	+ 0.0304 ns	+ 0.0611 **	
Pressure	+ 0.0012 ns		
Pressure Trend	+ 0.0014 ns		
Humidity	+ 0.0496 ns		
Humidity Trend	- 0.1035 **	- 0.0918 **	
Visibility	+ 0.0574 ns		
Cloud Cover	- 0.0917 *	- 0.0664 **	
Ceiling	+ 0.3883 **	+ 0.2639 *	
Precipitation	- 0.3122 ns		
SW Comp. Surface Wind	+ 0.0102 ns		
SE Comp. Surface Wind	- 0.0233 ns		
SW Comp. Wind Aloft	+ 0.0537 **	+ 0.0439 **	
SE Comp. Wind Aloft	- 0.0063 ns		
Correction Constant (K)	- 0.9468	+ 1.4310	+ 0.7730
Mult. Correl. Coeff. (R)	0.797 ***	0.773 ***	0.6870 ***
% Variance Explained (R^2)	63.6	59.7	47.2
Standard Error	1.32	1.30	1.44

[1] The analyses are based on data collected on 86 evenings. Scaling procedures for the predictor variables are described in Appendix B. Two-tailed significance levels are indicated as follows: ns, $p > 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

A positive constant indicates that the larger the value of the independent or predictor variable, the larger the value of the dependent variable. A negative constant, of course, indicates that there is an inverse relationship. The constants of any one of the regression analyses in table 1 may be combined with the appropriate independent variables in the predictive equation given above to obtain a forecast of the maximum altitude of the bat flight on the following evening. The independent variables, of course, must be scaled as in Appendix B. We recommend using the first stepwise model as it includes only six predictor variables and accounts for approximately the same proportion of the variance as the model including all the predictor variables. The second stepwise model is also of interest because it shows that a regression analysis involving a single predictor variable, the maximum altitude of the bat flight on the previous evening, accounts for 47.2% of the variance. It appears that on any given evening, the bats are likely to reach about the same maximum altitude as they did the evening before.

The relatively high percentage of the variance accounted for by the first stepwise regression model indicates that one can expect the predictive equation to provide fairly useful forecasts. It should be remembered, however, that the model only accounts for the variance in the cases upon which the analysis was based. The only real test of a predictive equation occurs when it is applied to new cases. Only by using the equations presented here can one determine if they are of value in forecasting evenings when low altitude bat flights are likely to occur.

SECTION V

EVALUATION OF THE BAT AVOIDANCE PROGRAM

It has proven impossible to obtain all the information necessary to perform a rigorous statistical evaluation of the efficacy of the bat avoidance program. Records distinguishing bat strikes, bird strikes, and collisions in which the animal was not identified were not kept prior to 1966. Also, we found that USAF regulations concerning documentation of nondamage strikes varied from year to year. Consequently, this evaluation is based only on collisions which resulted in damage to a T-38 engine or airframe. We wished to compute the yearly number of T-38 strikes which resulted in damage during months and periods of the day when bats were active, and to compare these figures across years. We found, however, that while we could obtain extremely well documented records of damage strikes, only records of the total number of T-38 flying hours per month were available. The information presented below in tables 2 thru 4 was obtained from the files of the 12th Flying Training Wing Flight Safety Office at Randolph AFB.

Table 2 shows the total number of T-38s damaged by bats, birds, and unidentified flying animals at Randolph AFB each year, from April thru October, from 1966 thru 1974. Note that exactly twice as many bats as birds were identified as being involved in collisions. This does not necessarily indicate, of course, that one third of the collisions in which it was not possible to identify the animal involved were bird strikes or that birds were involved in one third of the strikes which occurred during periods when bats were active. Table 3 shows the number of T-38s damaged by bats, birds, or unidentified animals at dawn (the 2 hour period after sunrise), during the

TABLE 2

NUMBER OF T-38S DAMAGED BY BATS, BIRDS, AND UNIDENTIFIED FLYING ANIMALS FROM APRIL THRU OCTOBER, FROM 1966 THRU 1974

Animals	Years									Totals
	1966	1967	1968	1969	1970	1971	1972	1973	1974	
Bat	2	0	2	8	8	3	6	1	4	34
Bird	0	1	0	5	1	3	1	3	3*	17
Unidentified	10	18	7	9	4	11	3	3	2	67
Totals	12	19	9	22	13	17	10	7	9	118

*One T-38 destroyed.

TABLE 3

NUMBER AND TYPE OF DAMAGE TO T-38S BY BATS, BIRDS, AND UNIDENTIFIED FLYING ANIMALS AT DAWN, DURING THE DAY, AT DUSK, AND AT NIGHT, FROM APRIL THRU OCTOBER, FROM 1966 THRU 1974

Animals	Type of Damage	Time of Day				Totals
		Dawn	Day	Dusk	Night	
Bat	Engine	3	0	0	31	34**
	Structural	0	0	0	0	0***
Bird	Engine	2*	2	0	4	8**
	Structural	0	7	1	1	9***
Uniden-tified	Engine	5	21	3	33	62**
	Structural	1	3	0	1	5***
Totals		11	33	4	70	118

*One T-38 destroyed.

**Total Engine Damage = 104.

***Total Structural Damage = 14.

day, at dusk (the 2 hour period before sunset), and during the night, from April thru October, from 1966 thru 1974. Table 3 also shows the number of cases in which an engine was damaged and the number of cases in which the airframe was damaged. Note that no bats were identified following strikes either during the day or at dusk. The majority of documented bat strikes occurred at night. Considering the schedule of pilot training operations at Randolph AFB and the timing and flight directions of bats leaving and returning to the Bracken cave (see Section III, IV), this is precisely what one would expect. Note also that bats have never been identified following damage to the airframe of a T-38. Initially, this finding might appear somewhat unusual. The identification of the remains of bats or birds after a collision with a wing, windscreen, or fuselage is usually accomplished more easily than when they strike an engine. Ingestions of bats or birds by turbojet engines frequently result in the virtually complete destruction of biological material. Mexican free-tailed bats, however, are small animals compared to most species of birds in the San Antonio area. It is likely that when these bats collide with a T-38 airframe, the impact is simply not severe enough to cause structural damage.

In view of the information presented above, we felt that the most reasonable approach to an evaluation of the bat strike program was to compare the number of bat and unidentified strikes which occurred at dawn and during the night across years. Table 4 presents this information. This table shows the number of dawn and nighttime strikes attributed to bats and unidentified animals per 1000 T-38 flying hours from April thru October, for each year from 1966 thru 1974. The table shows that the combined dawn and nighttime strike rate decreased markedly after 1967. This decrease coincides with the fact that during the early summer of 1968, nighttime and morning T-38 approaches to Randolph AFB were altered to avoid the immediate area of the Bracken cave

TABLE 4

NUMBER OF DAWN AND NIGHTTIME DAMAGE STRIKES ATTRIBUTED TO BATS AND UNIDENTIFIED ANIMALS PER 1000 T-38 FLYING HOURS FROM APRIL THRU OCTOBER, FROM 1966 THRU 1974

Years	Total T-38 flying hours (A)	Total dawn and nighttime bat and unidentified strikes (B)	Dawn and nighttime bat and unidentified strikes per 1000 T-38 flying hours (C)
1966	16630	9	0.54
1967	14008	14	1.00
1968	20261	7	0.35
1969	34801	12	0.34
1970	33198	10	0.30
1971	30607	8	0.26
1972	24432	7	0.27
1973	24253	1	0.04
1974	25321	6	0.24

Note: $C = B \div A \times 1000$

(see Section IV). There is also a suggestion in the data of a gradual decrease in the strike rate from 1967 thru 1974. This decrease coincides with the gradual introduction and refinement of real time, radar directed bat avoidance procedures (see Section IV). The data for 1973 and 1974, however, may not be directly comparable to those from previous years. A change in the nature of the training mission at Randolph AFB early in 1973 reduced the ratio of nighttime to daytime pilot training operations during both 1973 and 1974. Personnel at Randolph AFB estimate that this reduction was approximately 30% to 50%. It follows that figures shown in table 4 for 1973 and 1974 are a somewhat inaccurate, low estimate of the number of bat strikes during these years, and also that maximum possible strike rates could not be more than double those shown. The figures for these "worst possible cases" (twice those shown in table 4 for 1973 and 1974) are 0.08 and 0.48 respectively. The worst possible case for 1973 is well below that for any other year included in this evaluation. That for 1974 is lower than the strike rates for 1966 and 1967, the two years prior to the introduction of any bat avoidance procedures, but higher than the strike rate for any other year. It should be noted, however, that of the six strikes in 1974 attributed either to bats or unidentified flying animals during dawn or nighttime training operations, five occurred early during the "bat season" before radar avoidance procedures were in effect.

In summary, while it is not possible to demonstrate with certainty that the bat avoidance program was responsible for the decreasing strike rate shown in table 4, the data suggest that the program has resulted in considerable savings to the USAF, that the program should be continued, and that real time, radar avoidance programs may be of significant benefit in reducing bat and bird/aircraft collisions at other USAF installations.

SECTION VI

RECOMMENDATIONS

There can be no doubt that bats will continue to be a serious hazard to T-38 aircraft operating from Randolph AFB in the coming years. Collisions with bats could most certainly result in the loss of aircraft and the loss of life. There is no deterrent system known to us which is capable of clearing bats from runway areas or of causing bats to avoid aircraft. The USAF will have to determine what it considers to be an acceptable level of bat strikes. The effort and resources required to reduce the bat hazard will necessarily be a function of the desired level of strike reduction.

Our recommendations for the reduction of the bat hazard to aircraft at Randolph AFB are as follows:

1. Reduce nighttime T-38 flying operations to the absolute minimum during "bat season." If possible, transfer nighttime operations to another base. During the summer and winter, nighttime training could be carried out on cross-country flights. We do not recommend nighttime cross-country flights during the spring and fall, especially at altitudes of less than 3,000 m, because of the possibility of aircraft encountering the large numbers of migrant birds aloft during these periods.
2. Eliminate straight-in approaches near the Bracken cave from 2 hours before sunset until 2 hours after sunrise, unless radar observations indicate that this approach is necessary to avoid the bat flight.
3. Whenever the direction and velocity of the surface winds make it necessary for T-38s to launch toward the NW, we recommend that

nighttime training operations be canceled. Aircraft launching toward the NW during the hour after sunset are highly likely to encounter the bat flight from the Bracken cave. Fortunately, such wind conditions are rare and their occurrence can usually be forecast 24 hr or more in advance. It is unlikely that such wind conditions will occur on more than five evenings during any given "bat season" for which nighttime training operations are scheduled.

4. The radar based bat avoidance program, outlined in Section IV, should be continued. Specific instructions for tuning the MPN-14 and FPS-77 radars to detect bats are given in Appendix A. Above all, nighttime training operations should be halted and aircraft aloft diverted to another base whenever Type III flights are detected. Examples of each type of bat flight pattern are given in figures 8 through 10 of this report. Additional data should be collected concerning the relationship between the types of bat flights and the frequency of engine damage.
5. On evenings when low altitude (Type III) bat flights are forecast by means of the statistical procedures described in Section IV, we recommend that nighttime training operations be rescheduled. Comparing the actual maximum altitudes of the bat flights with the forecasted altitudes will eventually determine if this is a reasonable procedure.
6. Eliminate or reduce artificial lights and standing water on base wherever possible, and institute a strict insect control program.
7. Eliminate all bat roosts from buildings on base by repelling the bats from the roosts with napthalene flakes and then stopping up the cracks through which the animals gain entrance to the buildings.

8. Further attempts should be made to discover an effective bat deterrent system.
9. Personnel at Randolph AFB should keep separate records of the number of daytime and nighttime T-38 flying hours. This information would eventually allow a more accurate evaluation of the efficacy of the bat avoidance program.
10. The USAF should undertake a study to determine the best method of modifying the J-85-5 engines of the T-38 to withstand bat strikes. A study of the yearly costs of T-38 engine damage to the USAF may indicate that such a modification would result in considerable savings.

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APPENDIX A

INSTRUCTIONS FOR TUNING RADARS TO DETECT BATS

SAN ANTONIO INTERNATIONAL AIRPORT ASR-6 SEARCH RADAR

Antenna Elevation. -- 2.0°

Power. -- Maximum.

Radar Gain. -- Maximum.

Video Gain. -- Approximately 80%

Range. -- 20 miles. Plan Position Indicator display should be decentered 10 miles toward the SW.

Polarization. -- Linear. Circular polarization should be used only to reduce the returns from fog and precipitation. It should be noted that the use of CP will reduce the size of the bat echo.

Stability Time Control. -- Out to 5 miles.

Moving Target Indicator. -- Off. The MTI circuit should be used only on occasions when ground return is particularly heavy. Use of MTI usually results in a reduction in the size of the bat echo.

In the evening, the bats will first be detected at a point approximately 12 miles NE of the radar. In the morning, the bats usually approach the radar from the south. Morning bat radar targets have a diffuse, scattered appearance.

RANDOLPH AFB MPN-14 SEARCH RADAR

Antenna Elevation. -- 5.0°

Power. -- Maximum.

Radar Gain. -- Maximum.

Video Gain. -- Approximately 75%

Range. -- 20 miles.

Polarization. -- Linear.

Stability Time Control. -- Out to 3 miles.

Moving Target Indicator. -- Off.

In the evening, the bats will first be detected at a point approximately 11 miles NNW of the radar. In the morning, the bats usually approach the base from the south, producing a radar echo resembling a diffuse cloud.

RANDOLPH AFB FPS-77 WEATHER RADAR

Antenna Elevation. -- 0° to 90°

Altitude Scale. -- 0 to 30,000 feet.

Power. -- Maximum.

Radar Gain. -- Maximum.

Video Gain. -- Approximately 80%

Range. -- 15 miles.

Polarization. -- Linear.

In the evening, bats will first be detected at an azimuth of from 325° to 340°, at a range of approximately 11 miles. In the morning, the bat flight will usually first be detected at an azimuth of from 135° to 225° at a range of from 10 to 15 miles.

APPENDIX B

SCALING PROCEDURES FOR REGRESSION VARIABLES

DEPENDENT VARIABLE

Altitude. -- Maximum altitude of the bat flight in feet/1,000, measured with the FPS-77 weather radar at a point 5 mi NNW of Randolph AFB.

INDEPENDENT (PREDICTOR) VARIABLES

Date. -- Day of year (1 to 365).

Date^2. -- Day of year (1 to 365)^2/100. This procedure is often useful in avoiding round-off errors.

Altitude - 24 hr. -- Maximum altitude of the bat flight on previous evening in feet/1000, measured with the FPS-77 weather radar at a point 5 mi NNW of Randolph AFB.

Emergence - 24 hr. -- Time of appearance of bat flight on radar displays on the previous evening in minutes plus or minus sunset.

Temperature. -- Sunset value at Randolph AFB in ^{o}F.

Temperature Trend. -- Sunset value at Randolph AFB minus the sunset value on the previous evening in ^{o}F.

Pressure. -- Barometric pressure at sunset at Randolph AFB in inches of mercury to three places past the decimal point minus 29.0, times 1,000.

Pressure Trend. -- Barometric pressure at sunset at Randolph AFB minus the sunset value on the previous evening. Pressure is scaled as above.

Humidity. -- Sunset value in percent at Randolph AFB.

Humidity Trend. -- Sunset value at Randolph AFB minus the sunset value on the previous evening in percent.

Visibility. -- Sunset value at Randolph AFB in miles.

Cloud Cover. -- Proportion of sky covered by opaque cloud at Randolph AFB at sunset, in tenths, times 10.

Ceiling. -- 1 to 5 scale based on the altitude at which 6/10 total opaque cloud cover is observed from Randolph AFB. 1 = fog; 2 = < 2,000 feet but no fog; 3 = 2,000 to 5,000 feet; 4 = 5,000 to 10,000 feet; 5 = > 10,000 feet.

Precipitation. --- 1 to 3 scale based on observations of rainfall at Randolph AFB. 1 = no precipitation; 2 = showers at sunset; 3 = continuous precipitation or thunderstorms at sunset.

SE and SW Components of Surface Winds and Winds Aloft. -- The following component in knots per hour. Winds aloft are those at the 850 millibar level, estimated by comparing data obtained by radiosondes at Victoria, Midland, and Brownsville, Texas.