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Radio Tracking Puerto Rican Parrots: Assessing Triangulation Accuracy in an Insular Rain Forest

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ABSTRACT. – We evaluated the accuracy of a portable radio teIemetry system in an insular tropical rain forest in preparation for a long-term radio telemetry study of the critically endangered Puerto Rican parrot *(Amazona vittafa).* No significant differences were found among error biases when comparing receiver systems, transmitter heights, distances, and topographical inclinations. Error of bearings to transmitters placed at distances of 100 m and 200 m from receivers at ground and canopy levels averaged –1.12°. Error polygons ranged from 0.5 ha to 2.0 ha (at 100 m and 200 m distances, respectively). Error of bearings taken at long-range distances (0.9-2.8 km) and at elevated sites (mountain peaks and towers) providing "line-of-sight" access to test transmitters averaged 2.51". Error polygons ranged from 12.2 ha to 118.4 ha (0.9 and 2.8 km distances, respectively). Radio wave emissions from communication towers on prominent peaks occasionally reduced signal reception from ground-based receivers and completely masked signal reception in some valleys during aerial tracking operations.

RESUMEN. – Evaluamos la precisión de un sistema portátil de telemetric en un bosque pluvial insular tropical en preparación para un estudio de telemetric a largo plazo de la criticamente amenazada cotorra Puertorriqueña *(Amazona vittata).* No se encontraron diferencias significativas entre errores repetitivos cuando se compararon sistemas de recepción, altura del transmisor, distancias, e inclinaciones topográficas. El error en la lectura del transmisor localizado a distancias de 100 m y 200 m del recibidor al nivel de suelo y del dosel promediaron -1.12°. Los errores de los poligonos resultantes de las lecturas variaron desde 0.5 ha a 2.0 ha (a 100 y 200 m de distancia, respectivamente). Los errores tomados en lecturas de larga distancia (0.9- 2.8 km) y en sitios elevados (picos de montañas y torres) proveyeron un acceso visual para probar los transmisores, promediando 2.51°. Los errores de los polígonos resultantes de las lecturas variaron desde 12.2 ha a 118.4 ha (0.9 y 2.8 km, respectivamente). Emisiones de ondas radiales de torres de comunicación localizadas en picos prominentes redujeron ocasionalmente la recepción de la señal de los receptores a nivel terreno y eliminaron completamente la recepción en algunos valles durante las operaciones de rastreo aereo.

INTRODUCTION

Insular birds often occupy dense forest habitats, making them difficult to study. A prime example is the endangered Puerto Rican parrot (Snyder et al., 1987). This cryptically colored and secretive bird is arboreal, living in dense subtropical forest canopies that may reach heights of 30 m. Radio telemetry provides a technique to obtain data on this and other tropical forest species that otherwise would be extremely difficult or impossible to obtain.

Triangulation is a common telemetry method in which biologists obtain compass bearings to locate radio-marked animals. To determine the exact location of a radio-marked animal, the accuracy of bearings from triangulation and its associated error factors must be evaluated. Previous studies of location accuracy using triangulation have been conducted in continental temperate environments (Garrett et al., 1986; Heezen and Tester, 1967; Hupp and Ratti, 1983; Lee et al., 1985; Springer, 1979), a continental tropical forest (Dawson, 1979), and an insular temperate forest in New Zealand (Thomas, 1982). Montgomery et al.'s (1973) study is perhaps the only one to test the accuracy of a portable telemetry system in an insular, land-bridge

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tropical forest. They studied arboreal vertebrates on Barro Colorado Island in the Panama Canal Zone and reported that precise locations of radioed animals could be obtained only by walking to the tree they occupied.

To date, no studies have been conducted to test the feasibility of radio telemetry in insular forests on the high-relief, pelagic islands of the Caribbean, seven of which harbor endangered species of Amazon parrots. Moreover, accuracy of a telemetry system *must* be determined for *each* locale where a radio telemetry study is to be conducted. In this paper, we report the results of a series of tests conducted to evaluate the accuracy of a portable radio telemetry system in an insular rain forest as part of a long-term telemetry study of the Puerto Rican parrot.

STUDY AREA

The study was conducted in the Caribbean National Forest, a tropical rain forest located within the Luquillo Mountains of northeastern Puerto Rico (Fig. 1). The National Forest encompasses 19,648 ha and ranges in elevation from about 100 m to 1075 m. The topography is extremely dissected with steep upper slopes. The mountains include 5 life zones (Ewel and Whitmore, 1973) and are classified into four major vegetative associations, each roughly stratified by altitude: (1) palm forest located on steep slopes and arroyos above 450 m and dominated by the sierra palm *(Prestoea montana);* (2) tabonuco forest located below 600 m and dominated by the tabonuco tree *(Dacryodes excelsa);* (3) colorado forest located above 600 m and dominated by the colorado tree *(Cyrilla racemiflora);* and (4) dwarf forest located on peaks and ridges above 750 m and dominated by *Ocotea spathulata* and *Eugenia borinquensis* among other arborescent species. Annual rainfall varies from 300 cm in the foothills to more than 500 cm on the highest peaks. The annual average temperature is about 21°C (range = 11° to 32°C). A detailed description of the Luquillo Mountains is found in Odum and Pigeon (1970) and Wadsworth (1949).

METHODS

FACTORS AFFECTING TRIANGULATION ACCURACY-Bearing discrepancies include two components, error and precision. Error is the difference between the true bearing and the estimated bearing. An error of a consistent nature is termed bias and is the average difference between the estimated and true bearings. Precision is the amount of variation of estimated bearings and allows calculation of an area, termed the error polygon, within which the true location probably occurs (Springer, 1979). Estimates of a radio-marked animal's home range are directly affected by the size and shape of the error polygon. A common error factor that decreases bearing accuracy is signal reflection (or "bounce") caused by topography, vegetation, weather, interference from radio wave emissions and animal movement (Brewer, 1983; Hupp and Ratti, 1983; MacDonald and Amlaner, 1980; Springer, 1979).

TELEMETRY EQUIPMENT—Transmitters were low drain, 1-stage units (#LPB-1220-LD, Wildlife Materials, Inc.) (Reference to trade names does not imply endorsement by the U.S. Government). Transmitters weighed 4.5 g, had a 21-cm whip antenna, and a power output of –33 to –37 dBm. Frequencies ranged from 164.4375 to 164.7125 MHz. The three receiving systems included (1) model TR-2 (Telonics, Inc.) attached to a hand-held directional, 2-element antenna (model RA-2A, Telonics, Inc.) with a 40-dB gain and a 10-dB front-to-back ratio; (2) model Falcon 5 (Wildlife Materials, Inc.) attached to a miniature 3-element Yagi folding antenna (Wildlife Materials, Inc.); and (3) model TRX-24 (Wildlife Materials, Inc.) attached to a miniature 3-element folding antenna. The 3-element folding antennas had a 5.6-dB gain and a front-to-back ratio greater than 20 dB. Headphones were used to increase detection of weak signals and to determine signal locations.

STUDY DESIGN—Twenty sites were randomly selected within the Caribbean National Forest (Fig. 1) at elevations from 250 m to 790 m. Sites were located primarily within the colorado and tabonuco forest

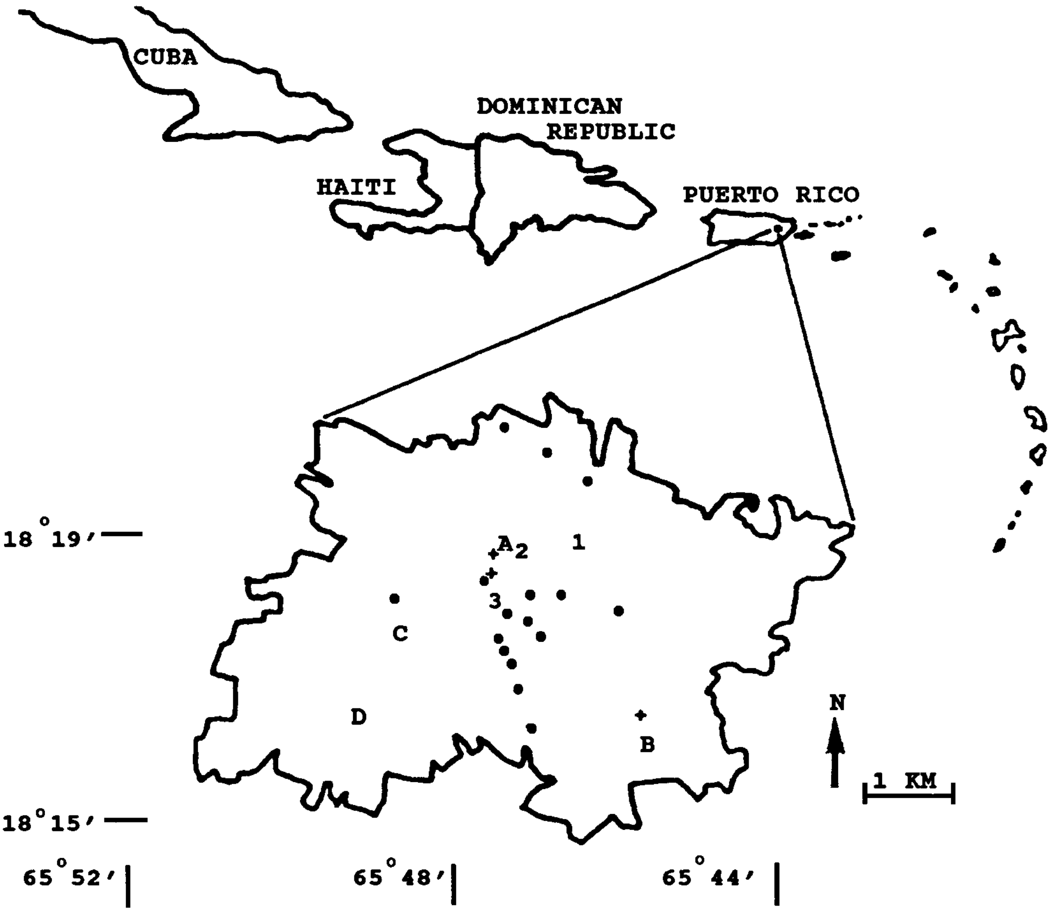

FIG. 1. Caribbean National Forest in northeastern Puerto Rico. Shown are major mountain peaks, observation and communication towers, and transmitter locations. A = El Yunque Peak (elev. 1065 m); B = East Peak (elev. 1050 m.); C = El Cacique Peak (elev. 1020 m.); D = El Toro Peak (elev. 1075 m.); 1 = Yokahu observation tower (elev. 507 m); 2 = Los Picachos observation tower (elev. 968 m); 3 = Mt. Britton observation tower (elev. 941 m); + = location of permanent communication towers in forest; ● = location of test transmitters.

zones, where most parrot activity occurs. Three sites were in the transition zone between the colorado and dwarf forests in areas containing palm brakes frequently used by foraging parrots.

Short-range telemetry tests were conducted. Transmitters were placed in trees to simulate signal reception and directional characteristics expected from units attached to canopy-dwelling parrots, which will also occasionally feed close to the ground. At 18 of 20 sites, a transmitter was placed in the understory at 2 m above ground level and another at canopy level (7-12.5 m high) in trees located at distances of 100 m and 200 m from, and at right angles to, forest roads. Transmitters were placed on the hillsides above the road at eight sites and below the road at 10 sites.

Transmitter signals were monitored using the loudest-signal method (Springer, 1979) at six receiver locations established along a 300-m transect that followed the road adjacent to each transmitter site. Three receiver locations were placed at 50-m intervals to the left, and three locations at 50-m intervals to the right, of the transmitter sites. Elevation of receiver locations ranged from 0 m to 80 m ($\bar{x}$ = 32 m) higher and 0 m to 100 m ($\bar{x}$ = 36 m) lower than locations of transmitters placed below and above forest roads, respectively.

Three observers, each using his own receiving system, obtained transmitter bearings from four to six locations along the 300-m transect for each transmitter. The meandering course of the mountain roads, the dense vegetation that hid the transmitters from view, and elevational changes of the forest terrain prevented the three study participants from knowing the location of test transmitters. Observers only recorded the direction of the loudest signal at each receiver location. Observers had from 1 to 20 years of experience, and each was pre-tested to assure familiarity and competence with telemetry procedures.

The remaining two sites (of the 20 total test sites) were established to evaluate long-distance signal reception and directional error. Transmitters were placed in trees using the same methods as previously described. Radio signals were monitored from prominent mountain peaks, ridges, and observation towers located 0.9-2.8 km from the transmitters. Receiving locations provided line-of-sight views to transmitter sites.

Direction of the loudest signal, indicating estimated transmitter location, was determined with a hand-held, Silva 15T compass. Potential errors associated with determining the direction of the loudest signal, reading of compass bearings by observers, and errors inherent in the receivers and antennas were not determined separately, but were included together with the error caused by signal reflection. Error was assigned a positive value between 0° and 179° clockwise from the true transmitter bearing and a negative value between 0° and 180° counter-clockwise (Hupp and Ratti, 1983). Data were collected between March 1986 and February 1987.

In addition to our ground-based tests, we flew over the Luquillo Mountains twice (October and November 1987) with a high-winged, twin-engine Cessna 336 to evaluate the use of aircraft to search for transmitter signals in our study area. One 3-element folding antenna was mounted in a side-looking position (Gilmer et al., 1981). A second antenna was mounted parallel to the wing strut, pointing downward to the ground at an angle of approximately 45 degrees in an attempt to reduce radio wave interference from communication towers located within the forest. Models TRX-24 and TR-2 radio receivers were used. Flight time was about 1 hr for each trip. A grid pattern allowed us to cover the forest and surrounding area three times. The airplane flew at elevations of 150 m and 300 m, at a speed of 100 mph. Three transmitters were placed at canopy level within separate valleys of the forest. In addition, two free-flying Puerto Rican parrots carried transmitters.

STATISTICAL ANALYSES—At 19 of the 20 sites (one site was eliminated because transmitter signals were not received by any of the three receiving systems), analysis of variance and Student's f-tests were used to test for differences in errors based on several effects, i.e., potential biases caused by receiver systems (equipment and observer), distance, height, and topography, Factors in the analysis, other than locations and receiver systems, were considered to be fixed effects. Locations were considered to be random effects and a blocking factor. Transmitters were assumed to be equal in all analyses (see Springer, 1979). Bartlett's test for homogeneity of variances was used to compare variance among treatments. Data were analyzed using SAS (Statistical Analysis System) (Helwig and Council, 1982) and SPS (Statistical Processing System) (Buyoff et al., 1985). Statistical significance was set at the 0.05 level in all analyses. Error polygons were calculated using the formula described in Hupp and Ratti (1983).

Results

Error bias resulting from the additive effects of signal reflection, radio wave emissions, receiver function, antenna configuration, and observers was negligible (Table 1) among the three receiver systems at both short range (100-200 m; $F = 0.327$, df = 2, 517, $P > 0.05$) and long range (0.9-2.8 km; $F = 2.71$, df = 2, 57, $P > 0.05$). Homogeneous variance was found among systems

TABLE 1. Error (difference between observed and true bearings in degrees) observed among bearings taken by three different receiving systems comparing the additive effects of signal reflection, receiver, antenna, and observer biases in the Caribbean National Forest, Puerto Rico, 1986-1987.

Receiver system	n	x	SD	Range
Short range (m)[a]				
Telonics	177	–2.70	14.63	–43-+53
Falcon 5	158	2.46	21.37	–67-+128[b]
TRX	185	–2.40	20.40	–74-+76
Long range (km)[c]				
Telonics	23	0.04	5.75	–11-+15
Falcon 5	23	2.17	6.23	–9-+13
TRX[d]	14	2.92	5.61	–11-+16

[a] 100 and 200 meters.
[b] Extreme signal reflection.
[c] 0.19, 1.8, and 2.8 km.
[d] Analysis does not include two extreme bearing errors (–35° and +57°) for the TRX receiver system when heavy radio wave emissions from communication towers reduced signal reception.

(Bartlett's $X^2 = 4.26$, df = 2, $P > 0.05$). Therefore, receiver systems were assumed to be equal (see also Springer, 1979) in subsequent analyses testing for potential biases among distance, height, and topographical features.

Error bias of bearings to both short and long range transmitters was negligible (Table 2) ($F = 0.38$, df = 1, 518, $P > 0.05$ and $F = 2.87$, df = 2,57, $P > 0.05$, respectively). Homogeneous variance was found among the two short range and three long range distances (Bartlett's $X^2 = 5.56$, df = 2, $P > 0.05$ and Bartlett's $X^2 = 2.72$, df = 2, $P > 0.05$, respectively).

TABLE 2. Error (difference between observed and true bearings in degrees) observed among bearings taken from transmitters placed at different distances in the Caribbean National Forest, Puerto Rico, 1986–1987.

Distance	n	x	SD	Range
Short range (m)				
100	299	–0.72	27.57	–67-+76
200	221	–1.82	20.81	–74-+128[a]
Pooled	520	–1.12	19.35	–74-+128
Long range (km)				
0.9	23	4.09	7.67	–35[b]-+16
1.8	23	–0.71	5.27	–11-+10
2.8	14	3.57	6.36	–7-+5[b]
Pooled	60	2.51	10.99	–35-+57

[a] Extreme signal reflection.
[b] Extreme radio wave emissions interference from communication towers.

TABLE 3. Error (difference between observed and true bearings in degrees) observed among bearings taken from transmitters placed at different heights in the Caribbean National Forest, Puerto Rico, 1986-1987.

Distance[a] and height[b]	n	$\bar{x}$	SD	Range
Short range (m)				
2 m	349	–1.74	18.68	–74-+128[c]
Canopy	171	–0.19	17.00	–51-+49
Long range (km)				
2 m	23	2.26	9.59	–35-+16
Canopy	37	2.67	11.56	–11-+57[d]

[a] Short range = 100 and 200 meters. Long range = 0.9, 1.8, and 2.8 kilometers.
[b] One transmitter was placed on tree trunks 2 m off the ground and another at canopy level (7-12.5 m) at both short- and long-range distances.
[c] Extreme signal reflection.
[d] Extreme radio wave emissions interference from communication towers.

Error bias of bearings to transmitters placed at different heights (2 m off the ground and canopy level) was also negligible (Table 3) at both short and long range distances ($t = 0.92$, df = 364, $P > 0.05$ and $t = 0.14$, df = 58, $P > 0.05$, respectively). Homogeneous variance was also found among the two sampled heights ($F_{max} = 1.16$, df = 348, 170, $P > 0.05$ and $F_{max} = 1.51$, df = 36, 22, $P > 0.05$, respectively).

Topographical inclination (slope bias) was investigated comparing errors between ascending (up slope) and descending (down slope) transects. Data are as follows: up slope $n = 228$, $\bar{x} = -3.00$, SD = 15.10, range = – 74-+38. Down slope $n = 292$, $\bar{x} = 0.04$, SD = 18.80, range = –68-+ 128 (this last figure indicates extreme signal reflection). Heterogeneous variance was found ($F_{max} = 1.43$, df = 291,227, $P < 0.05$) and so a t-test for unequal variance was used. Slope bias was also negligible (t = 1.90, df = 517, $P > 0.05$).

Pooled error from all bearings to transmitters located 100 m and 200 m from receivers and at heights of 2 m and canopy level averaged – 1.12° (SD = 19.35°) (n = 520, range = –74°-128°) (Table 2, Fig. 2). The sizes of the calculated average error polygons were 0.50 ha at 100 m and 2.0 ha at 200 m assuming perpendicular triangulation from points equidistant from receivers.

Pooled error from all bearings to transmitters located 0.9 km, 1.8 km, and 2.8 km from receivers and at heights of 2 m and canopy level averaged 2.51° (SD = 10.99°) (n= 60, range = –37°-+57°) (Table 2). The average sizes of the calculated error polygons were 12.2 ha, 48.9 ha, and 118.4 ha at 0.9 km, 1.8 km, and 2.8 km, respectively.

Radio wave emissions from communication towers located on El Yunque Peak (Fig. 1) and elsewhere in the forest masked reception of transmitter signals in some valleys and reduced receiver sensitivity to signal reception in all areas during searches conducted by aircraft. The method of mounting the antennas did not reduce radio wave interference. During the first flight, two of three test transmitters and one of two radio-marked parrots were located. On the second flight, two of three test transmitters were located, but neither of the radio-marked parrots was found. Ground monitoring confirmed that one radio-marked parrot on the first flight, and both radio-marked parrots and one test transmitter during the second flight were within valleys where interference from communication towers completely masked signal reception.

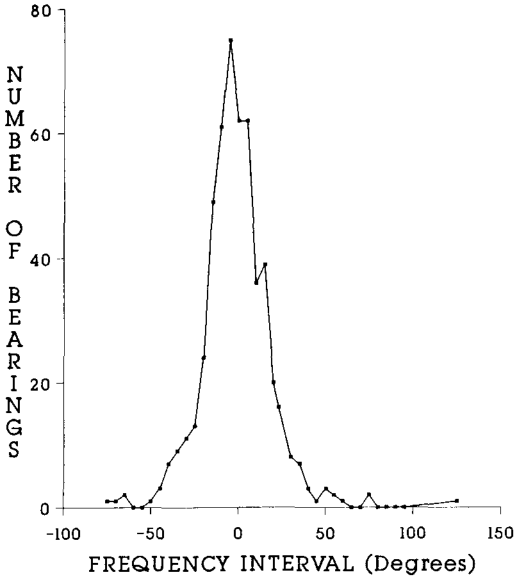

FIG. 2. Frequency of estimated bearing errors (n = 520) to test transmitters located in trees 100 m and 200 m from receivers and at heights of 2 m and canopy level (7-12.5 m) in the Caribbean National Forest, Puerto Rico, 1986-1987. The distribution free 80% tolerance interval is from – 23° to +23°, i.e., with 90% confidence, 80% of the error distribution is between these values.

DISCUSSION

Our results showed that errors resulting from a multiplicity of inherent and introduced biases and physical factors can be minimal in tropical forest ecosystems, even in rugged terrain. Average bearing errors and error polygons obtained in this study provide a general understanding of the effects of triangulation errors expected when tracking radio-marked animals within the Luquillo Rain Forest. Error biases and sizes of error polygons derived from both short-range a-rid long-range receiver-to-transmitter distances using portable receiving systems were similar to those reported for temperate forests (Brewer, 1983; Hupp and Ratti, 1983). Error polygons derived from signal bearings taken at distances of 100 m to 0.9 km (0.5 -12.2 ha) are small enough to accurately evaluate macro-habitat use by parrots.

Although bias associated with slope of the terrain was not significantly different at the 5% level, the relative high significance level ($P < 0.10$, t = 1.90) suggests that it might be an important bias factor under some circumstances. However, there was no immediate explanation of why there might be significant error biases between ascending and descending terrain, other than the obvious possibility of physical interference of signal reception caused by intervening vegetation or topographical features such as hilltops and rock outcrops.

The dense tropical vegetation and rugged topography common to montane rain forests, and characteristic of the Luquillo Rain Forest, obstructed our view of test transmitters in all cases. Ridges, undetected because of the dense vegetation, occasionally formed physical barriers between the transmitter and observer and blocked signal reception. These factors, along with the extremely wet climate and radio wave emissions from communication towers, influenced signal reception, strength, and direction.

In 150 of 670 attempts to monitor signals from receiver locations along forest roads, we were not able to detect transmitter signals. On five occasions, signal reflection, caused primarily by steep banks along roads, caused peak signals to be received simultaneously from two directions. On another occasion signal reflection caused the observed signal direction to change 128” from the true direction.

Tester (1971) stated that signal reflection was not a serious problem in his studies because an experienced observer could detect and modify his study technique accordingly. In our studies, we also found that extreme changes in observed signal direction caused by signal reflection could be determined and eliminated by experienced observers using field maps. When signal reflection was suspected, bearings could be taken at three or more locations then drawn on the field maps to determine which of the bearings was suspect.

Methods for using and increasing the accuracy of radio telemetry in temperate forests, discussed by Cochran (1980) and MacDonald and Amlaner (1980), were applicable in our tropical rain forest.

Radio wave emissions from communication towers located on El Yunque Peak (elevation 1065 m) and elsewhere within the Luquillo Mountains interfered with signal reception at some of our ground sites and seriously affected radio tracking by aircraft. During periods of heavy use, emissions from these towers often completely masked transmitter signal reception at our vantage points on Mt. Britton, Los Picachos and East Peak. At other times, interference caused signal reception to be minimally audible. Santana and Temple (1984) also reported interference from communication towers while tracking Red-tailed Hawks *(Buteo jamaicensis)* in the Luquillo Mountains.

In Hawaii, Harrison and Stoneburner (1981) experienced interference while monitoring radio signals but did not state the source of their interference. We found that moving receiver locations to areas with an intervening ridge to the towers effectively eliminated nontarget interference. Also nontarget radio wave transmissions from towers were heavier at certain times of the day. Determining the periods of heavy and light radio wave emissions allowed us to determine when exposed receiver locations could best be used.

Interference with the reception of transmitter signals caused by communications towers during radio tracking by aircraft rendered this method ineffective in our study. Such signal interference could prove to be a serious hindrance to aerial tracking techniques on other high-relief islands in which communications equipment is mounted on prominent peaks. Under such circumstances, researchers need to determine the amount of interference caused by communications towers and the best methods to circumvent this problem before initiating telemetry studies. If radio wave emission interference cannot be effectively eliminated, radio telemetry may not be a research option on some islands.

We recommend that biologists considering studies using telemetry in tropical islands conduct tests to thoroughly evaluate potential sources of error and logistic problems that they will encounter before initiating actual monitoring studies. Establishing a workable tracking system can be accomplished only as one becomes familiar with the study species and the terrain it inhabits.

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