DEVELOPING ACOUSTIC TELEMETRY SYSTEMS FOR TERRESTRIAL MAMMALS: A BRIEF PROGRAM HISTORY

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1 INTRODUCTION

This paper summarizes a 20+ year saga in which a technologically naïve wildlife biologist pursues a seemingly modest technological objective. Namely, an electronic system for remotely monitoring the behavior of individual free-ranging mammals from the audible sounds they produce. After all, mammals and other vertebrates do generate a variety of sounds that are diagnostic of specific activities[1,]. And in an age of advanced electronic applications in biology, suitable technology should have been readily available. In fact, acoustic technology did exist for sounds generated by other vertebrates, notably birds[2] and marine mammals[3].

Why then a saga, and not a smooth success story in the case of terrestrial mammals? First, for this biologist, the effort obviously demanded a stout bridge across the biology - engineering divide; specifically, the collaboration of electronic engineers that might find the subject compelling. Secondly, an "ideal" comprehensive wildlife acoustic telemetry system would comprise an amalgam of four sub-systems: (a) a compact microphone transmitter that could be unobtrusively mounted on subject animals, (b) a field-worthy acoustic data receiving and recording system, (c) a catalogue of behaviorally diagnostic sounds for the species of interest, and (d) a capability for machine classification of behaviors based on sound signal properties[4]. Third, because no suitable commercial systems were available, they had to be created specifically for this undertaking. Finally, both the interest in and funding available for terrestrial mammal acoustical telemetry were limited, especially in contrast to the resources available for marine mammal programs.

Here I will trace my acoustic telemetry pursuits chronologically, beginning with crested porcupine research in the 1980's, and concluding with current efforts with cattle and future plans. Although the word "program" appears in the title, this quest followed an irregular path, often more characteristic of a hobby than the smooth trajectory of a well designed and well funded scientific program. My efforts in acoustic telemetry were largely shaped by the availability of time, and of human, material and animal resources.

2 PHASE 1: DESERT PORCUPINES

Indian crested porcupines (Hystrix indica) are large nocturnal rodents, distributed across a wide band of central Asia. In Israel's Negev desert, porcupines are highly dependant on belowground plant biomass for food, and are adept in excavating tubers, bulbs and rhizomes during nightly foraging bouts. Ecological research at the Blaustein Institute of Desert Research revealed that porcupine digs were excellent microhabitats for plant germination, and that soil displacement by porcupines had profound effects on soil, water and vegetation dynamics in Negev landscapes[5]. As opportunistic foragers, porcupines also depredated a wide range of agricultural crops in the Negev[6] and elsewhere in Israel.

Because little was known about the biology of the animals themselves, I undertook field and laboratory studies of crested porcupine behavior and ecology beginning in 1981. Using standard radio-location telemetry, we defined year-round patterns of porcupine temporal and spatial activity[7,8] in the Negev highlands. We also measured porcupine impacts on agricultural crops[9] and on natural habitats[10]. The research yielded interesting insights on porcupine behavioral ecology in desert environments. For example, we found that these den-dwelling animals avoided exposure to moonlight in winter such that their above ground activity was concentrated during darker periods of winter lunar cycles. They also traveled further from dens on dark than on brighter moonlit nights[5]. However, moonlight avoidance waned in late spring and disappeared by summer when porcupines were active throughout the night. Nightly activity averaged 9.3 hr in summer, as compared to 7.5 hr in winter. Why the seasonal shift in temporal activity? We hypothesized that shorter nights of summer lunar cycles did not offer sufficient moonless hours for porcupines to adopt a dark-only activity regime, and so the animals abandoned a moonlight avoidance strategy.

Radio-location telemetry informed us where and when porcupine above-ground activity took place, but provided no direct evidence of what the animals were doing. We experimented with light enhancement and infrared optics for visually monitoring porcupine behavior at night. Neither approach proved useful. Light enhancement optics did not yield sufficiently distinct images for behavior research, and infrared light resulted in obscuring reflectance from vegetation. Both methods also required close-range observation, thereby potentially affecting the animals' behavior. How then were we to monitor porcupine field behavior?

An acoustic approach suggested itself when I finally grasped the fact that our captive porcupines were generating audible feeding sounds, threat huffs and quill shakes. A few years earlier, in fact', a New Zealand team had described a self-designed acoustic transmitter for relatively close-range field studies of brush-tailed opossums[11]. Pursuing this possibility, we managed to assemble a workable acoustic telemetry system comprised of inexpensive, off the shelf components. These were a small battery powered acoustic body transmitter ("bugging device") purchased from a local security firm, a standard FM radio/tape recorder, and headphones. With the transmitter suspended close to an individual animal or mounted on a collar, we used this system to record sounds generated by penned porcupines, and later by leash-led subjects that were trained to accompany us in the field. Our simple equipment revealed that porcupines produced an array of audibly distinctive sounds, including biting, chewing, drinking, sniffing, huffing, quill rattling, locomotion, and digging[4]. We could also distinguish among several food types. Blind audio tests with colleagues confirmed that nearly all recorded porcupine behaviors were recognizable. Indeed, acoustic telemetry seemed to offer a powerful alternative for monitoring very detailed behaviors of terrestrial mammals, including those that could not be reliably detected and counted by vision or the naked ear alone.

Our first working prototype, however, had a limited transmission range and was not sufficiently robust for use with free-ranging animals. We then turned to one of our radio-location telemetry suppliers, Cedar Creek Bioelectronics Lab (now Advanced Telemetry Systems) for a custom-built a field-worthy prototype meeting the following specifications: transmission of good quality sounds at a range of ≥ 500 m in open terrain, individually unique FM transmission frequencies, a transmitter life-span of ≥ 1 week, and a field receiver with tape recorder, antenna and head phone outlets. The Cedar Creek transmitter we received operated at a fundamental mode of 18.8 MHz, had an electret condenser microphone, a 30 cm antenna, and was powered by two lithium D cells in series with a calculated life span of span of 400 hr. These components were embedded in dental acrylic and mounted on a sturdy machine belt collar. The standard Cedar Creek tracking receiver was modified to detect FM radio signals. Using a vehicle-mounted 2-element Telonic precision antenna at 2.5 m elevation, or a hand-held 5-element Telonics antenna, we field tested this system in open desert terrain. We consistently detected and recorded good quality acoustic signals (human voice, recorded music and porcupine sounds) at ≤ 1,000 m distance using head phones. Signal quality rapidly deteriorated at longer distances. As hoped for, this second prototype demonstrated an enhanced potential for field application.

With the collaboration of of Ben-Gurion University's Biomedical Engineering Center, we also undertook to examine sound signal properties of various porcupine behaviors[4]. First, digitized 5-sec acoustic segments of known behaviors were plotted for total sound energy. Next 3-dimensional spectrograms (sound energy versus frequency at 51 msec time steps) were derived for selected feeding behaviors, demonstrating that sound signal properties visibly differed among even similar behaviors. Statistical analyses also revealed that feeding, walking, and sniffing sounds could be automatically classified using a 2-sec delayed decision algorithm applied to carefully selected, noise-free segments. A more sophisticated 3-level weighted decision algorithm showed promise for dealing with environmentally noisy segments that are more typical of field recordings. In all, these exploratory analyses suggested that machine classification of porcupine sounds was a feasible goal. Such a capability would minimize the considerable labor investment that would be required to manually classify behaviors from large sound signal data files.

3 PHASE 2: SABBATICAL IN THE STATES

3.1 FORT COLLINS, COLORADO

In 1990-91 I took a year sabbatical leave from Ben-Gurion University, the first half of which was spent at Colorado State University. One of my sabbatical aims was to determine whether acoustic telemetry offered promise for monitoring other mammal species. Before leaving, I had good results with acoustically monitoring dog behavior, but poor results with a collar mounted transmitter on captive Nubian ibex (Ibex nubiana). My test animals In Colorado were captive northern collard lemmings (Dicrostonyx groenlandicus), black-tailed prairie dogs (Cynomys ludovicianus), Rocky Mountain bighorn sheep (Ovis canadensis), and steers (Bos taurus). To assure accurate behavioral classification of animals sounds, we recorded visual and audio signals simltaneously in these tests.

To this end, we employed an RCA Prowonder Video Camcorder for visual records and a Realistic (Radio Shack) FM Wireless Microphone transmitter and receiver for sound. A Magnavox Stereo AM/FM Recorder and Realistic stereo headphones were also used. Of the species tested, only prairie dogs did not produce consistently audible feeding signals. Lemmings, by contrast, generated very rapid, clear biting sounds while feeding on herbaceous vegetation and solid food items. For both prairie dog and lemmings, sounds were captured with a microphone suspended in their small enclosures. Considering the failure of my earlier Nubian ibex acoustic tests in Israel, perhaps the most interesting Colorado results were those with the two large ruminant species. Steers held in a barn transmitted clear diagnostic sounds for a range behaviors including sniffing, chewing hay, chewing pellets, regurgitating boluses and rumination chewing, drinking, exhaling methane, and vocalizing. With a bighorn ewe held in an outdoor enclosure, and feeding on herbaceous vegetation and pellets, we obtained clear and consistent sounds of sniffing, tearing and chewing herbaceous vegetation, chewing on pellets, drinking, and deep respiration during warm periods, As in the porcupine tests, most of the steer and bighorn sounds were not detectable by the naked ear, and detailed feeding components were not reliably detected by vision.

Why our success with ruminants in Colorado but not previously with ibex? The answer was in microphone placement. Following our porcupine work, a research team at the University of

California-Davis conducted very successful acoustic feeding experiments with cows[12]. They discovered that microphone placement on the brow of the cow's skull consistently resulted in the transmission of high quality audio signals. They readily counted bites and chews, and even estimated intakes of grass forage by cows from the sound energy generated by chewing[13]. Consequently, we also adopted head placement of the microphone for our steer and bighorn tests. In this procedure we attached a microphone to a shaved patch on the subject's forehead with duct tape, and taped the transmitter to a neck collar. A cable connected the mike and transmitter. As with collars alone, this configuration was readily accepted by subject animals. Head microphone placement also proved successful and non-intrusive in our later tests with other ungulates.

3.2 PULLMAN, WASHINGTON

The second half of my sabbatical was spent at Washington State University (WSU) where my acoustic telemetry attention shifted from rodents and ungulates to bears. I experimented with penned black bears (Ursus americanus) maintained by the Wildlife Research Program on campus, and with grizzly bears (U. arctos horribillis) held in large outdoor enclosure at the Walk in the Wild Zoo[14]. My objectives were to create a catalog of behaviorally diagnostic sounds produced by captive bears, and to develop an acoustic transmitter collar suitable for bear field research. We obtained simultaneous visual and audio records of bear behavior; and the principal equipment used was a Pansonic camcorder and a Realistic FM Wireless Microphone and receiver. From my earlier porcupine and dog trials, I assumed that a collar-mounted microphone configuration would suffice for bears. We conducted five trials during the study, three with an adult male black bear held in a sheltered outdoor metal pen, and two with a young adult female grizzly bear in the large outdoor enclosure. The animals were chemically immobilized for placement of collars, were fully recovered when acoustic trials were conducted. Between trials, we evaluated the results and made incremental adjustments in equipment and protocols.

For the black bear tests, a collar mounted 6" length of 2-1/2" diameter automobile hose served as the transmitter package. For grizzly bears we built a more robust laminated PVC housing that resembled commercial wildlife telemetry collars. Disassembled microphone transmitter components and batteries were inserted in the housing. In both configurations, the microphone was situated at a small hole in the housing close to the bear's throat. All equipment modifications were performed by the WSU Technical Services Department.

Our results were mixed[14]. The final black bear trial produced good quality sounds of feeding and other behaviors, although the auto hose equipment housing was not judged to be a satisfactory platform for field use. The PVC housing used in the grizzly bear trials was robust and structurally sound. However, it failed acoustically in the first trial when the bear submerged in a large water basin. Our attempts to waterproof the housing and microphone opening resulted in degraded acoustic signals in the final grizzly trial. A previous test run of the waterproofed transmitter package, but with the polypropylene diaphragm covering of the microphone removed, did result in high quality acoustic transmission at distances of ≥ 150 feet. With my sabbatical at an end, there was no opportunity to make additional alterations that might well have resulted in a satisfactory prototype collar for bears, and a more complete catalogue of black and grizzly bear sounds. That said, bears appear to be excellent candidates for acoustic telemetry research. They produce a range of behaviorally diagnostic sounds, and are capable of carrying large acoustic telemetry packages with sufficient battery power for extended use.

4 PHASE 3: FROM NEW MEXICO AND BEYOND

4.1 DESERT MULE DEER

In 1996 I moved from Ben-Gurion University in Israel to New Mexico State University (NMSU) in the U.S. Early sporadic forays in acoustic telemetry eventually led to a grant funded research project on penned desert mule deer (Odocoileus hemionus eremicus) held at the University of Arizona in Tucson[15]. My Arizona collaborators were associated with the School of Renewable Natural Resources, and we had invaluable engineering support from the Physical Sciences Lab at NMSU. One of our aims was to employ a more sophisticated acoustic system in monitoring mule deer behaviors. The inexpensive wireless system used in the sabbatical experiments (above) transmitted good quality sound signals, but was not robust and often generated strong feed-back signals when the animal subjects were close to fencing or other metal structures. In this study, we sought to acoustically record as wide a range of deer behaviors as feasible, and to compare head- versus collar-mounted options for microphone placement in deer.

The principal components of our system were a Sony Handycam digital camcorder and a Samson Airline Wireless Microphone System (including antenna-equipped microphone transmitter and receiver) designed for professional entertainment purposes. For the collar-mounted microphone placement, we disassembled the Samson transmitter components and had them housed (by Telonics Inc.) in an aluminum case with a screened opening for exposure of the unidirectional condenser microphone. The aluminum container was attached to a machine-belt collar. For the head-mounted microphone configuration, we connected a separate Samson omni-directional lavellier microphone to the transmitter via a cable that extended from the collar-mounted transmitter to a shaved patch on the rear of the deer's skull. A modified plastic 4 cm diameter suction cup attached with SuperGlue was used to hold the microphone in secure contact with the deer's head. We also augmented transmitter and receiver battery power to extend the system's operating life. Trials were held with three penned deer in which the animals were offered several types of food. Visual and audio signals were recorded on Sony Hi8 MP video tapes.

We collected 1,500 minutes of simultaneous visual-audio behavior records that encompassed feeding, drinking, walking, ruminating, ear flapping, grooming and urinating events[15]. Foods tested were alfalfa hay, alfalfa pellets, deer chow, oak and manzanita browse, and dried white mulberry leaves. We found that the head-mounted microphone configuration resulted in more complete and higher fidelity audio signals than the collar mounted microphone. The latter often allowed us to distinguish feeding from other behaviors, but not to acoustically identify separate components of feeding (mouthing, biting, intake chewing, rumination chews) or specific forages consumed, as was possible with the head mounted microphone. Even the use of a professional grade audio system did not render a collar-mounted microphone satisfactory for uninterrupted monitoring of more detailed ungulate behaviors in large ungulates. We also concluded that the equipment array used in this study did provide a simple, relatively inexpensive and powerful means of remotely monitoring foraging and other behaviors of deer at distances ≤200 m. The system would be very useful for acoustic studies of domestic stock and of confined or relatively tame wildlife. Two other points are worth mentioning. First, in blind audio tests, wildlife students consistently recognized feeding and drinking events by sound alone, and achieved ≥ 90% accuracy in identifying four of the six forages tested[15]. We also undertook some computer-based analyses of deer sound signals. In one procedure, filtered 10-30 sec sound segments of deer feeding bouts were examined for acoustic waveform patterns by Praat Speech Analysis software. The mean elapsed time between successive impulses (ETBI) were compared by ANOVA for food type and individual deer. Using Matlab software, we also analyzed the spectral content of high fidelity records of various behaviors. We compared autospectrums for energy peak frequencies, and calculated frequency response functions (FRF) for each behavior. These analyses proved somewhat promising. ETBI's differed significantly among three forage types for which suitable data were available; and there were large differences in FRF's between feeding and drinking events, and among some forage types. We concluded that a much more focused effort was needed to develop machine classification of ruminant behaviors by sound.

4.2 LISTENING TO LIVESTOCK

Our studies of mammals to date were on leash-led subjects or individuals held in small or large enclosures. Following the mule deer study, and with little funding support, I sought to determine the maximum distance that available acoustic equipment might achieve under field conditions. Substantial improvements in acoustic range would increase the species and field conditions under which acoustic telemetry might be usefully employed. By this time, successful close-range (<200 m) acoustic telemetry field studies had been conducted on wild tammar wallabies (Macropus eugenii)[16] and koalas (Phascolarctos cinereus)[17]. We conducted lab and outdoor equipment tests on the NMSU campus, and field experiments with cattle at the Jornada Experimental Range (JER).

Following a series of equipment modifications and six field experiments at JER, with and without cattle, we achieved a mobile acoustic system that acquired high quality, continuous human voice and animal feeding sound signals from a microphone-transmitter at distances of ≥ 3.5 kms (1.8 miles) in open rangeland. Our equipment array consisted of three subsystems as follows.
Microphone transmitter and collar: The transmitter was a disassembled Samson Airline UHF Wireless Microphone including a transmitter (with antenna) operating at 803 MHz. A Shure Subminature Condenser Lavilier microphone was used because of its small size and thin profile. The power source were two alkaline D-cell batteries in series, and all components were housed in an aluminum box with two drilled holes for entry of the microphone cable and the transmitter antenna cable connections. The transmitter pack was attached by duct tape to a double-layer nylon collar fitted around an animal's neck. The microphone was enclosed in a small plastic frame that was attached with SuperGlue to the subject's shaved brow with the microphone's sensitive side in contact with the animal's skin, and then covered with duct tape. To further enhance signal strength we (a) mounted the transmitter antenna on the dorsal apex of the collar, that was connected to the transmitter by a 0.1" coaxial cable, and (2) inserted a 2"x 6" thin copper foil between the two layers of nylon in the dorsal area of the collar to serve as a ground plane.
Receiver sub-system. We used a 10-element Maxrad directional antenna mounted on a 19-ft Maxrad telescopic mast as the signal acquisition heart of the mobile receiving sub-system. The antenna mast (and all other system components) was readily transported in a field vehicle, and could be rapidly erected by a by a two-person team. The base of the antenna mast was inserted in a hollow tubular stand with a projecting leaf that was held in place by one of the vehicle's tires The antenna was connected to a radio frequency Low Noise/High Gain preamplifier with a Bias Tee; and the coaxial cable from the preamplifier was connected to a power injector and a modified Samson wireless receiver in series, both powered by a 12 V, 7.2 amp/hr rechargeable battery. A Radio Shack mini amplifier/speaker was also connected to the receiver.
Signal recording and data storage sub-system: A Panasonic Toughbook laptop computer with built-in soundcard and NCH Swift Sound software was connected to the Sampson receiver (above). The computer was powered by a 12 V lead acid automobile battery that was continuously recharged by a Siemens 55 w solar panel connected by a power inverter to the laptop. An Automatic Sequencing Charger served as a control between the solar panel and laptop computer.

Applied as an experimental prototype, our system transmitted strong, clear and continuous audio signals with little or no interference at 3.2 km (2.0 miles) line of sight between the transmitter and receiver in open rangeland. At ≤ 3.5 km (2.2 miles), signal strength declined slightly but overall audio quality was still good. At 3.8 km (2.4 miles), signal strength was faint and static stronger; and

4.5 km (2.8 miles) audio was very degraded. However, pending physical modifications this system was not considered sufficiently robust for prolonged use under field conditions. Necessary improvements would include more protected and secure connections between electronic components, more rugged transmitter and receiver components, a more reliable sound signal recording system, and better microphone attachment to the animal's cranium. I did not have the resources to implement these modifications.

5 THE FUTURE

We are now preparing a research proposal that would incorporate integrated acoustic and GPS telemetry in a study of field energetics of free-ranging cattle in New Mexico rangeland. Because the animals will be handled weekly, we will not be constrained by energy demands (batteries for operating the data collection component can readily replaced) nor by the need to remotely acquire sound signals (time-stamped acoustic and GPS data will be stored on replaceable memory sticks carried by the animal). We would also attempt to develop an automatic behavior classification system for cattle based on algorithms employed in advanced speech and voice recognition technology [18]. If successfully implemented, the system we develop may be the first to satisfy the criteria for a comprehensive "ideal" telemetry system outlined in the Introduction, Only two firms to my knowledge produce commercial acoustic transmitters for large animal research, i.e., Sirtrack in New Zealand and Bluesky Telemetry in Scotland.

Challenges remain in acoustically monitoring wild terrestrial mammals that are far ranging and that cannot be handled at convenient intervals. An obvious constraint is the large energy demands of continuous sound signal transmission in relation to the limited battery packs that can be easily carried by most mammals. Potential approaches for minimizing or ameliorating transmitting energy demand may include; remote on-off switches, programmable operation schedules, signal compression and transfer, enhanced data storage capacity, and even perhaps improved batteries. Aerial and satellite telemetry offer opportunities for acoustically monitoring far-ranging animals in combination with location determinations. My bottom-line recommendation to fellow technologically challenged wildlife biologists is to get hold of an interested engineer, apply your field smarts, and let your imagination soar.

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