Satellite and Ground Radiotracking of Elk

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RADIOTRACKING AND MONITORING of free-living animals in natural environments is providing an effective new technique for acquiring information on biological processes, including animal orientation and navigation. To test the practicability of extending the technique by using satellite systems for tracking animals, a female elk was instrumented with an electronic collar. It contained both the Interrogation Recording Location System (IRLS) transponder and a Craighead-Varney ground-tracking transmitter. The elk was successfully tracked and monitored by satellite during the month of April 1970. This was the first time an animal had been tracked by satellite on the surface of the Earth. Information derived from the present feasibility study provides a basis for assessing uses of the system, reducing the weight, and improving the configuration of the instrument collar for monitoring a variety of large mammals. The minimum weight of the IRLS transponder, even with microminiaturization, makes its use impractical for most small mammals and birds. A doppler-shift type of satellite system, as described by Maxwell at this conference, may prove effective for small animals.

This project was a joint endeavor between the Smithsonian Institution and the National Aeronautics and Space Administration, conducted in collaboration with the Montana Cooperative Wildlife Research Unit, the Environmental Research Institute, the State University of New York at Albany, and the National Geographic Society. Pretesting was conducted at the National Bison Range, Moiese, Montana. The experiment was carried out at the National Elk Refuge, Jackson Hole, Wyoming, in cooperation with the U.S. Bureau of Sports Fisheries and Wildlife, the Wyoming Game and Fish Commission, the U.S. Forest Service, and the National Park Service. Previous research under NSF (G-17502) made possible the use of the ground radiotracking system.

HISTORY OF PROJECT

The present project had its inception on May 26, 1966, at a conference sponsored jointly by the Smithsonian Institution, the

American Institute of Biological Sciences, and the National Aeronautics and Space Administration (ref. 1). At this time the possibilities for using the Nimbus meteorological satellites for tracking and monitoring wild animals were explored by biologists and engineers. An initial estimate of 11.3 kg for the IRLS instrument platform proved accurate. This transponder was heavy for use on wild animals, as it had been designed for oceanographic buoys and high-altitude weather balloons. It was apparent that a large animal would be required for the first experiments in satellite tracking of free-roaming animals. However, engineers calculated that the weight could eventually be reduced by 50 to 75 percent. An elk was chosen for the first test because of its large size (about 225 kg), gentleness, and migratory behavior. In addition an accumulated background of experience in radiotracking and immobilizing elk (ref. 2) was available over a period of years in the Jackson Hole–Yellowstone National Park area. Logistic support for the project was particularly favorable in the Jackson Hole area.

A planning conference was held May 9–12, 1969, in Missoula, Montana, at which time biologists and engineers decided on the configuration and packaging of the IRLS transponder and selected parameters to be monitored. A Craighead-Varney transmitter was packaged with the IRLS transponder since this ground-tracking system had a capability that enabled observers to visually locate the elk, thus providing direct observations with which to measure the accuracy of satellite positioning. This 32.0 MHz tracking system had been used to successfully track six cow elk for a total of 1216 animal tracking days. In addition, one elk had been radiotracked from the National Elk Refuge to its summer range in Yellowstone National Park, a distance of 64.4 airline km.

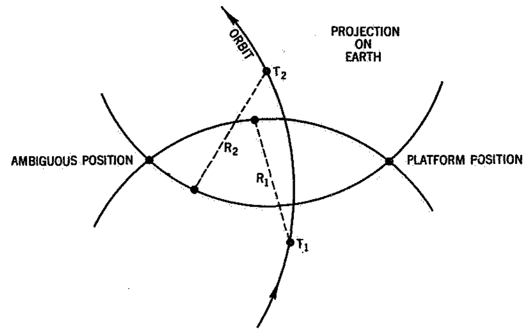

FIGURE 1. IRLS location technique: Distance (R_1) between satellite and instrument platform generates a sphere with satellite at center (T_1): this sphere in space intersects the Earth in a perfect circle. Second perfect circle intersecting first at two points is formed by second interrogation at T_2. Platform position is readily selected on basis of prior information from previous orbits.

MATERIALS AND METHODS

The experiment was carried out with the Nimbus III and IV satellites, using the IRLS system to locate and interrogate the animals (refs. 3 to 5). The IRLS instrument was designed with 28 channels of communication, 10 of which were used in the present experiment. One IRLS instrument was modified and packaged into the collar for the elk, with batteries as the source of power and solar cells to maintain battery charge. To conserve power, a timing system provided a 10-min window for transmission during satellite overpasses. The radio transmitter power output was 15 W to the antenna at a frequency of 466.0 MHz.

The Nimbus satellites are in polar-sun-synchronous orbits, and their exact position above the Earth can be calculated. The distance between the satellite and elk was determined by a radar-like interrogation. This line generates a sphere, with the satellite at the center, that forms a perfect circle where it intersects the Earth's surface. Another circle is formed by the second interrogation, intersecting the first circle at two points. The animal is located at one of these two points; the other point is sufficiently distant from the animal, as determined by prior information, to be considered unlikely as the animal's position (fig. 1).

The Craighead-Varney ground-tracking transmitter (32 MHz) was installed in the lower compartment of the collar. Batteries and antenna for this system were located at the top of the collar.

The instrument collar was separable into two parts for installation on the elk. Instrumenting was accomplished when the animal was immobilized with M99 (etorphine). Ten min were required to make the electronic connections and fasten the collar on the elk.

Internal telemetry for the instrument was provided by five sensors, and external data were monitored by another five sensors. The data format corresponding to the computer printout is shown in figure 2. One such frame of data was collected during each interrogation of the instrument. For each overpass the satellite was programmed for up to five interrogations at intervals of 1.5 min. Data were available to the experimenters within 1 to 2 hr of the overpass. The pressure transducer for measuring altitude failed and was inoperative throughout the experiment. Skin temperature was measured by a thermistor mounted on a tension arm attached on the inside surface of the collar. Battery voltages and temperatures were monitored directly, and the received signal strength was obtained at the output of the first intermediate frequency stage. Two thermistors provided overlapping scales (—40 to + 10 °C; 0 to + 50 °C) for measuring ambient temperature within ± 1 percent accuracy. For additional information about the IRLS system see Craighead et al.

An electromechanical timer-control unit provided a 6-month battery lifetime by completely unloading the battery during the 12-hr intervals between orbital overpasses. During each overpass a 10-min "power on" period was initiated precisely as the satellite came into radio view. The timer setting of the window was monitored on each orbit, and periodic adjustments were made by command from the satellite to maintain synchrony.

```
        DATE OF RUN      MO.   DAY   YR.
                          4     28    70
        ORBIT NUMBER     5082
        PLATFORM ID    105452         ELK

   COMMAND TIME   HH   MM   SS.S
                  07   54   10.6
   FRAME                1

                 DATA RECEIVED

  2  UNUSED                   1  UNUSED
  4  ALTIMETER                3  UNUSED
  6  +12 VOLT BATTERY         5  RECEIVER SIGNAL
  8  BATTERY TEMPERATURE      7  SKIN TEMPERATURE
 10  -40 TO +10°C AMBIENT     9  0 TO +50°C AMBIENT
 12  TIMER                   11  +4.8 VOLT BATTERY
  |                          13  LIGHT INTENSITY
  | }UNUSED                   |
 28                           | }UNUSED
                             27

           COMPUTED PLATFORM LOCATION

                                    TIME
   LAT.       LONG.         DAY   HH   MM   SS.S
 43.492N    110.721W        118   07   54   11.0
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FIGURE 2. Data format showing arrangement of data on computer printout forms.

PROCEDURE

During the summer and fall of 1969 a mockup model of the instrument collar was developed and tested on four female elk in a corral at the National Bison Range. The collar (11.3 kg) weighed less than known weights of elk antlers. None of the elk experienced any apparent interference with daily activities, and there was no evidence of breakage of hair or skin abrasions from rubbing of the collar during feeding activities. One elk carried the collar for a period of 90 days without difficulty. Pretesting of the electronic instrument collar began on January

20, 1970, using the same female elk after it had been without the mockup collar for about 2 weeks. The pretest was highly successful in terms of placing the instrument collar on the elk and interrogating the instrument daily for the next 12 days on 16 orbits of the satellite.

On February 5, two female elk at the National Elk Refuge were immobilized and fitted with mockup collars to pretest the reaction of these animals to the collar prior to instrumentation.

On February 19, an effort was made to place the IRLS collar on one of the two females wearing the mockup collars. The elk were uneasy as a result of a census of the herd made earlier that morning, and the experimental animal was difficult to approach. Considerable maneuvering was required to get one of the females within range of the immobilizing gun. The shot made at long range (60 to 70 m) missed the intended elk and struck another female in the herd. She became immobile in about 5 min. This female appeared to be a healthy individual, and except for preconditioning to the collar, equally well suited for the experiment as either of the females wearing mockup collars. Since conditioning did not appear to be essential, the instrument collar was fastened to this elk with the assistance of electronic engineers. The female recovered quickly upon receiving the antidote M285 (diprenorphine) after being immobile for 30 min. The female then rose to its feet without difficulty, stood momentarily looking at the haywagons and observers without apparent alarm, and then ran to rejoin the herd. The satellite was unable to communicate with the instrument collar for the first 3 days, apparently because installation of the instrument package had occurred during the hourly 6-min speed-up cycle, which in turn disrupted the orbital period setting of the timer. By special command from the satellite the timer was reset, and at noon on February 22, data were received from the animal. Subsequent passes failed to yield data. Visual observations of the elk indicated that she remained bedded down for abnormally long periods of time, walked sluggishly, and was not feeding. The female finally died on the morning of February 23, apparently of pneumonia which is not uncommon in the herd on the Refuge. The stress of being captured may have aggravated an incipient infection.

On April 1, 1970, one of the two females originally fitted with a mockup collar was instrumented with the IRLS equipment (fig. 3). A veterinarian ascertained the health of the animal. Her body temperature was normal (38.5 °C) and she appeared to be in good condition. She became immobile 5 min after administration of the M99 drug and remained immobile for about 27 min, during which time the dummy collar was removed and the electronic collar was attached. Immediately after the antidote was injected the

FIGURE 3. IRLS instrument collar on female elk tracked in April 1970. Antenna housing is at top and solar panels are on side of collar.

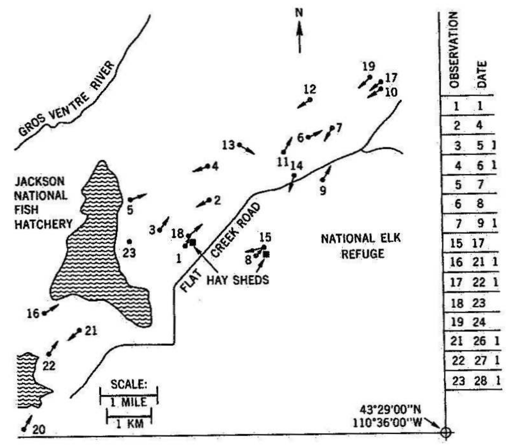

FIGURE 4. Locations of instrumented elk from direct observation or fixes with Craighead-Varney ground-tracking system. Accuracies were within 0.5 km. Errors in satellite fixes were computed against these observations. Arrows indicate direction of following observation.

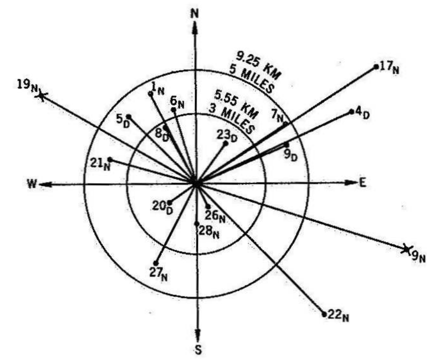

FIGURE 5. Visual observations vs satellite positions.

female was placed on her brisket. Within 3 minutes she arose, looked around briefly at the observers and then nibbled at a nearby bale of hay. The instrumented female then walked off about 25 m, stopped, and then slowly ran off to join the herd about 200 m away. When she joined the herd she immediately had an encoutner with another female. Both elk rose on their hind legs and paddled gently with their forelegs. Such behavior seems to establish dominance-subdominance relationships between individuals within the herd. This incident and the immediate acceptance of the instrumented elk by other members of the herd indicated that the process of immobilizing and instrumenting had not been traumatic and that the female returned to normal behavior almost immediately after recovering from the drug. Within the next hour the instrumented female was observed feeding, standing, and walking with the herd.

The elk had recovered and joined the herd by 10:50 a.m. At approximately 11:00 a.m., Nimbus III passed over the Jackson Hole area and the IRLS collar transmitted location, skin and air temperatures, and five parameters of the IRLS instrument (table 1).

RESULTS

The resolution of locations determined by the satellite varied considerably. In order to measure the accuracy of the locations it was necessary to derive a set of reference points from field observations of the elk. Orbital overpasses were approximately at noon, and some of the observation times did not coincide exactly with satellite overpasses, making some interpolation necessary in deriving the set of reference points. The reference points made on the ground are shown in figure 4. The magnitude and direction of location errors determined by satellite are shown in figure 5. Three locations were beyond the scale and were not included in the figure. Excluding these three points the mean errors were 4.8 km in latitude and 6.2 km in longitude. The large east-west errors (longitude), which were typically less than the north-south errors (latitude), reflected the fact that

TABLE 1.—*Locations and Sensory Data from Elk at National Elk Refuge*

Orbit no.	Date	Time (GMT)	Location: lat.	Location: long.	No. frames	Channel 5: Signal strength volts	Channel 6: +12 volt battery °C	Channel 7: Skin temperature °C	Channel 8: Battery temperature °C	Channel 9: 0°C to +50°C ambient temperature	Channel 10: −40°C to +10°C ambient temperature	Channel 11: +4.8 volt battery	Channel 12: Timer (min)	Channel 13: Light intensity [a]
Nimbus III														
23	Apr. 1	07:49:13	43.62	110.74	4	1.15	12.45	<15.5	+5.0	<0.0	−5.5	5.1	5 to 6	6.35
27	Apr. 1	18:07:08	43.51	111.14	3	1.00	12.8	<15.5	+5.0	<0.0	−1.5	5.25	6 to 7	2.45
40	Apr. 2	07:05:14			1	.25	12.95	24.0	+.5	<0.0	−4.5	5.35	5 to 6	6.35
53	Apr. 3	08:07:55			1	.20	13.55	<15.5	+7.0	+1.0	0.0	5.55	4 to 5	2.35
67	Apr. 4	17:43:45	43.588	110.69	3	.10	13.4	19.5	+5.0	+1.0	+.5	5.5	5 to 6	2.55
80	Apr. 5	18:47:44	43.617	110.78	3	.85	13.4	20.3	+12.5	+10.0	+8.5	5.5	4 to 5	2.40
91	Apr. 6	07:47	43.607	110.73	4									
03	Apr. 7	02:04:09	43.594	110.598	4	.30	13.25	20.5	+4.5	+1.0	+.5	5.35	5 to 6	6.35
18	Apr. 8	08:05:29.2			1	.15	13.3	<15.5	−2.0	<0.0	−7.5	5.35	3 to 4	6.35
21	Apr. 8	18:24:08	43.602	110.678	5	.95	13.65	24.0	+9.0	+2.0	+1.5	5.55	4 to 5	2.65
30	Apr. 9	07:23:44	43.501	110.402	5	.85	13.55	23.5	+1.5	<0.0	−6.0	5.5	5 to 6	6.35
34	Apr. 9	17:40:29	43.589	110.543	4	1.00	13.65	27.8	+8.5	+2.5	+2.0	5.55	4 to 5	2.75
Nimbus IV														
	Apr. 10	18:46:00			2			34.5	+8.0	+5.0	+4.0	5.4	3 to 4	2.95
	Apr. 10	07:44:30			1			37.5	+3.0	<0.0	−1.5	5.2	5 to 6	6.35
	Apr. 17	18:01:00			1			27.8	+4.5	+4.5	+4.0	5.4	4 to 5	3.3
Nimbus III														
4913	Apr. 15	18:39:40.1			1		13.75	27.5	11.0	2.0	1.5	5.60	4 to 5	2.10
4937	Apr. 17	06:58:5.4	43.621	110.485	4		13.30	27.6	3.0	<0.0	−4.0	5.40	7 to 8	6.35
4950	Apr. 18	07:59:16.5			1		13.15	20.0	3.0	<0.0	−2.0	5.35	4 to 5	6.35
4964	Apr. 19	07:17:47.3	43.604	110.852	3		13.15	25.0	1.5	<0.0	−4.0	5.35	6 to 7	6.35
4981	Apr. 20	18:37:43.3	43.517	110.696	3		13.75	26.5	6.5	1.0	0.5	5.60	4 to 5	2.45
4988	Apr. 21	07:37:3.9	43.545	110.794	3		13.55	25.0	−2.5	<0.0	−8.0	5.35	4 to 5	6.35
4995	Apr. 21	17:55:8.6	43.52	110.32	3		13.55	22.0	12.5	1.5	0.5	5.40	5 to 6	3.00

Orbit no.	Date	Time (GMT)	Location		No. frames	Channel Numbers								
						5	6	7	8	9	10	11	12	13
			lat.	long.		Signal strength volts	+12 volt battery °C	Skin temperature °C	Battery temperature °C	0°C to +50°C ambient temperature	−40°C to +10°C ambient temperature	+4.8 volt battery	Timer (min)	Light intensity [a]
5001	Apr. 22	06:55:12.5	43.480	110.553	2		13.25	25.5	−1.0	<0.0	−6.5	5.25	6 to 7	6.35
5015	Apr. 23	07:58:4.9			3		13.25	22.0	1.0	<0.0	−4.5	5.30	5 to 6	6.35
5022	Apr. 23	18:16:28.4	43.568	110.652	4		13.65	30.3	13.5	6.5	6.5	5.40	5 to 6	2.50
5029	Apr. 24	07:12:33.0	43.579	110.267	5		13.15	24.5	2.5	<0.0	−3.0	5.20	3 to 4	6.35
5055	Apr. 26	07:34:17.3	43.492	110.712	3		13.25	<15.5	4.5	1.5	1.5	5.10	3 to 4	6.35
5069	Apr. 27	06:53:19.7	43.452	110.783	3		13.25	28.5	2.0	<0.0	−3.0	5.30	5 to 6	6.35
5075	Apr. 27	18:56:7.0			1		13.55	27.8	8.5	3.0	3.5	5.45	1 to 2	2.55
5082	Apr. 28	07:54:10.6	43.492	110.721	4		13.40	32.2	2.0	<0.0	−2.0	5.30	2 to 3	6.35

[a] 6.35 = night; 2.10 to 3.00 = varying degrees of sunlight

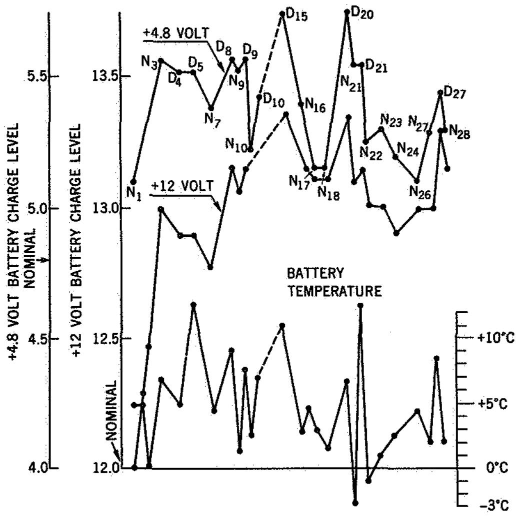

FIGURE 6. Satellite monitored day-night battery voltages and temperatures.

satellite locations are most accurate when the satellite is between 10 and 50° above horizontal. The dipole antenna used in the elk experiment was designed for a coverage above 45° with respect to the horizontal. In future experiments the accuracy of locations can be improved with a low profile, omnidirectional, circularly polarized antenna.

The monitoring of sensors showed the potentialities of the IRLS system for obtaining physiological and environmental information (table 1). The voltage levels of the batteries increased during the first 3 days, showing that the solar panels were responsible for charging the batteries. The charge levels remained near maximum throughout the experiment. The trends in battery and ambient temperatures were identical (fig. 6). Some warming was probably provided by the elk's body. In previous studies of the effects of ambient air temperature on radio collars the battery pack and transmitter have shown an average 9.4° C increase over air temperatures under cold weather conditions. This was attributed to the warming effect of the animal's body (refs. 6 and 7).

The accuracy of measuring skin temperature with a thermistor at the point of contact between the collar and the animal's body requires further testing to determine the effects of the collar in compacting the hair and insulating the thermistor, as well as the effect of movement of the collar during feeding activity. Individual skin readings taken at 1.5-min intervals during interrogation sequences suggest that the animal was at rest when the readings were constant and active when the readings were variable (table 2). Apparently movement of the collar altered its insulating effect, producing more regular temperature readings when the elk was at rest. The exceptionally high skin temperature (37.5° C), which was near body temperature, on April 10 could have resulted from continued pressure of the elk's neck against the thermistor as the animal lay on its side with its neck resting on the collar. In a similar manner a skin temperature of 35.9° C was recorded from an awakened and alert black bear in its winter den as it lay on a thermistor located

TABLE 2.—*Multiple Interrogation Skin Data*

	Elk at rest (°C)		Elk moving (°C)
April 9, night...	23.6	April 7, night.	18.6
	23.6		20.5
	23.3		20.3
	23.0		19.7
	23.0	April 9, day...	27.8
April 17, night..	28.0		27.2
	28.3		28.1
	28.3		23.0
	28.3	April 23, day..	30.9
April 21, night..	25.0		30.0
	25.5		30.3
	25.5		29.9

between the animal's body and the insulating material of its bed (ref. 2). An inverse relationship between skin and ambient temperatures, shown in about half the recordings (fig. 7), could reflect a decrease in insulation of the elk's integument due to compaction of the hair under the collar. The significance of the data is that they show the potentialities for studying thermoregulation by monitoring surface and subcutaneous skin temperature, along with deep body temperature, using the IRLS system.

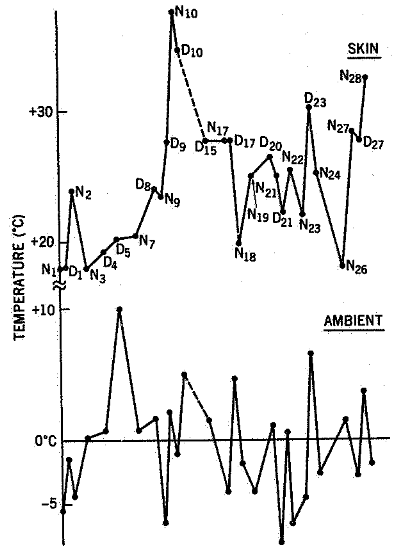

FIGURE 7. Satellite monitored skin and ambient temperature readings.

MOVEMENTS OF THE ELK

Except for the longer movements, the locations obtained with the IRLS system were too inaccurate for determining the local pattern of movement of the elk within the Refuge. However, satellite location of the elk could have yielded useful new information on migratory movements despite the low resolution. The collar rotated around the elk's neck on May 1 and, in the inverted position, contact between the elk and the satellite was lost. Communication proved impossible with the antenna pointing groundward. Until June 10, the elk was located by the ground-tracking system. When the elk moved far or rapidly it was relocated by air, using a Cessna 150 with a small loop antenna attached to the wing strut. Under favorable conditions the signal was received in the airplane from a distance of up to 40 km at altitudes above ground level of 300 to 1000 m; the strength of the signals improved with altitude.

On May 15, the elk moved to the northern portion of the Refuge and was approached, using the directional receiver. She was observed to feed and run well with a band of 15 elk, and she appeared in better physical condition than most of the other elk. Two days later she left the Refuge, moved north along the east side of Blacktail Butte, and arrived the following day in the area of Signal Mountain, 28 airline km from her last position in the Refuge. After remaining here and in this general area for 5 days the elk began moving up Spread Creek on May 25, traveling southward into the Gros Ventre drainage (fig. 8) to Slate Creek where a group of about 300 elk annually calve and range for the summer months (ref. 8). The circuitous route taken by the elk to reach its summer range, covering about 65 km, rather than traveling directly up the Gros Ventre River valley for a distance of about 20 km, was unanticipated. The route taken also involved crossing a high divide that was still snowbound.

As the instrumented elk migrated, the number of elk with which she was associated gradually diminished with distance and time away from the National Elk Refuge. On the Refuge she was a member of a scattered herd of 3000 to 4000 animals, and this number diminished to an average of 250 to 400 animals.

FIGURE 8. Gros Ventre River drainage to which elk migrated from Refuge. Loop antenna, shown at top of the photograph, was used to communicate with ground-tracking system.

On May 15, two days before leaving the Refuge, the elk traveled with a group of 15 animals. On May 23, and from time to time thereafter, she was observed alone or with only one other cow. From this latter behavior we suspected the imminence of parturition.

From May 30 to June 10, sightings and radio fixes indicated that she moved only an average of 1.1 airline km per day with a range of 0.2 to 1.9 km. This was a considerable reduction over her previous daily travel, and might have been related to calving. A close observation on June 8 established that the elk was in good condition, that most of the winter coat remained, and that no abrasions or sores caused by the collar were evident. It also appeared that the cow was not pregnant. A calf was not observed at this time, but could have been hiding, since it is a common practice of calves to hide when danger is imminent (ref. 9). Possibly the decrease in daily movement as indicated by radiotracking was a clue to time of calving. Such noticeable changes in daily movement as revealed by radiotracking, when properly interpreted and then verified by observation, can provide insights to animal activity and behavior. For example, intermittent signals from instrumented grizzly bears have been visually confirmed as an indication of den digging (ref. 10).

An interesting result of the elk's summer movements is that she was more or less constantly traveling, spending only a few days to a few weeks in any one area or drainage. The elk was last located by the ground-tracking radio on June 10. The next contact was a sighting on July 28 in the Cottonwood drainage about 20 km east of Slate Creek. The probable route of her travels (a gradual movement) after leaving the Slate Creek–Mount Leidy area was eastward to the confluence of Poison Creek with Cottonwood Creek. On November 14, she was accidentally shot by a hunter 8 km from this location and just prior to her expected safe return to the National Elk Refuge.

Daily movement of the elk on the Refuge that occurred before migration averaged 3.7 km, based on 41 movements, and ranged from 0.6 to 14.6 airline km. Just prior to a long trek on April 24, ground-tracking showed that the elk had traveled an average of about 2.6 airline km per day. On April 25, she backtracked 14.6 km toward the Refuge feeding lots (fig. 4). This was the longest single trek prior to migratory movement. Such movement back and forth in response to weather and snow cover is typical during April. However, this return travel started before a storm arrived and may have been in response to an approaching storm. The barometer dropped, and snow fell for the next two days.

Some animals apparently can sense an approaching storm. A change in activity associated with an approaching snow storm was clearly demonstrated while radiotracking an instrumented grizzly bear to its winter den. This grizzly altered her previously recorded daily activity pattern one morning and started moving rapidly toward her den in bright, sunny weather. Snow started to fall in late afternoon, and the female grizzly arrived at her pre-excavated den that evening (ref. 10). Apparent early detection of weather changes by both bear and elk is intriguing and may be related to the animals' possible ability to detect infrasound waves created by approaching but distant storms (ref. 11). Satellite as well as ground radiotracking should be a useful tool in probing this phenomenon in wild animals, perhaps even under controlled conditions.

Changes in the elk's activity and their interpretation, as well as the migratory observations, indicate that behavior and migration of individual elk can be studied in detail with the aid of radiotracking and biotelemetry ground-satellite systems. These studies can provide information of value in the management of elk populations, as well as contribute toward a better understanding of the phenomena of animal behavior and migration.

RESULTS

The study was successful in demonstrating the practicability of tracking large free-roaming animals in natural environments by satellite systems. The prototype IRLS instrument collar was somewhat bulkier and heavier than required, and on the basis of information derived from monitoring the instrument by satellite, particularly the effect of the solar cells on battery charge, calculations indicated a possible weight reduction of about 50 percent down to about 5 kg. A fin antenna is now available for the instrument, which would eliminate the large housing required for the dipole antenna and reduce the profile of the instrument. Variable padding with foam rubber to adapt the instrument to a given elk would solve the problem of the collar turning around on the elk's neck. An improvement in the resolution of locations to within 1 km would be possible with the development of a low profile, omnidirectional, circularly polarized antenna. Experimentation with effective sensory systems is needed to measure deep body temperature, skin temperature, heart rate, and other physiological parameters. To eliminate external wiring, implantable transmitters are required for transmission of data to receivers in the instrument collar. Miniaturized equipment for periodic data sampling and storage prior to transmission (every 12 hr) is needed.

The advantages of satellite systems are described elsewhere (ref. 12). Briefly, satellites permit daily tracking and monitoring on a worldwide scale with instruments that are immune to the effects of Earth's weather and provide data under day or night conditions. Where animals are isolated in polar regions, the oceans, or deserts, satellites are especially useful. To obtain adequate data on bird migrations over long distances and at high altitudes or marine animals covering great distances, satellite systems are almost indispensable. The uniqueness in satellite systems lies in the ability to combine continuous tracking up to 6 months, or longer, with simultaneous monitoring of physiological and environmental parameters.

Despite the advantages of satellites, radio contact with animals from the ground is also needed for homing in on animals for direct observations. An integration of the two systems is likely to be required in most research.

An accurate system for tracking free-living animals and monitoring both physiological and environmental parameters will provide a valuable new tool for investigating the behavior and ecology of wild animals. Satellite systems can aid in investigating a vast array of important biological problems, including migratory movements and navigational guidance mechanisms of animals, patterns of dispersal and concentration associated with feeding and reproduction, the entrainment of physiological cycles by environmental parameters, and patterns of vector transmission of disease by migratory animals (ref. 12). The knowledge gained through such studies will help provide the scientific basis for intelligent management of the Earth's ecosystems.

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The IRLS instrument was conformed into the collar for the elk by Radiation, Inc., Melbourne, Florida.

Tracking animals by satellite was stimulated by Sidney R. Galler, Assistant Secretary (Science), Smithsonian Institution, who organized the 1966 conference on this subject. We are grateful for his encouragement and inspiration. George J. Jacobs, Chief, Physical Biology, National Aeronautics and Space Administration, was particularly helpful in the development and administration of the project.

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DISCUSSION

COCHRAN: You have called this a feasibility study. Is it practical to conduct a study on the elk?

BUECHNER: Yes indeed, I think it is practical. We know the weight can be reduced at least one half, without doing any miniaturization. We also know how to make a better configuration for the collar and we have some ideas on how to improve the antenna system. The costs can come down. In fact, potentially, if there are enough users, the costs could come down very quickly to something around $2000 or $3000 per instrument package.

We hope that next year we will be able to track an elk during the spring migration and make periodic ground observations to correlate behavior with migration movements and physiological parameters.

ENRIGHT: There may be a slight difference in the elevation of the animal which could make a big difference in the apparent geographical location. Is this a real problem?

COTE: The elevation is certainly a factor; we do not assume that the Earth is a perfect sphere. In the case of the elk, changes were in the order of 90m (300 ft) which did not greatly impact location accuracy. For high flying balloons or aircraft tracking applications the altitude becomes a critical factor and must be entered into mathematical equations for location computation.

WILLIAMS: You state that your readings extended over eight to ten minutes for one point. How is this possible?

COTE: Since the satellite is in view for 4 to 5 min, multiple interrogations lasting 2 sec each are programmed. This allows up to five data samples under normal operational conditions where 1 minute intervals are maintained. The two frequencies utilized in the IRLS system are 401.5 and 466.0 MHz.

CARR: Did resolutions in your track-plots for the elk correspond to those for the buoy? That is, do you get about the same fineness in separating and locating points with the elk as you would in tracking the buoy?

COTE: No. The buoy positions were more accurate since higher power equipment was used. Under these conditions the satellite need not be directly overhead to obtain solid communication. Optimum location accuracies with the higher power equipment are obtained at elevation angles between $+5$ and $+50°$ with respect to the horizontal.

SLADEN: How did you measure skin temperature?

COTE: Readings of external skin temperature were obtained by a thermistor mounted on a tension arm attached to the collar. The tension was calibrated to enable skin contact under normal activity conditions.

QUESTION: Do any of you object to using a harness?

CRAIGHEAD: Initially, we considered a harness but rejected it for a number of reasons. The elk really has a very strong neck. We didn't have many problems with collars reversing in the initial tests.

BULLOCK: There is a source of power that has not yet been mentioned. This is the piezoelectric source. Currently engineered devices obtain energy from the organism via its movements and produce about ⅕th or ⅙th of a mW power continuously with very high efficiency. It would be a negligible load for an ordinary bird in terms of extra work, to deflect a piezoelectric crystal to produce a milliwatt. The advantage is that you are getting away from any prepackaged foreign power source and are dealing with an endogenous source of power.

The device, for instance, which Carl Enger (ref. 13) has been using in dogs takes some of the work from the respiratory muscles which bend a small device, about 30 grams in weight, a cylinder about 50 mm long and 10 mm in diameter. The main element is a piece of ceramic which is deformed very slightly. This deformation produces the power—a relatively high voltage (around 20 V) at low current. From this particular device they are getting about 300 microwatts continuously.

What would be needed to increase the power to one milliwatt is another gram of weight increasing the bulk from 30 to 31 grams. This would add enough ceramic material so that about a milliwatt could be obtained continuously. The problem becomes where to attach the device. They are working now loose in the pericardium, deformed by the beating heart, and fixed to the vertebrae and ribs, deformed by respiratory movements. This puts the problem back to the biologist where it really belongs. There is essentially a negligible loading in respect to weight and to work.

The point is, that with this small a device you could radiate milliwatts continually and interrogate the animal every minute or every hour, instead of compromising with an interrogation once a week.

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