2-P
M1X

PROGRESS REPORT

NASA Research Grant NGR 27-002-006

DEVELOPMENT OF SATELLITE-RELATED BIOTELEMETRY EQUIPMENT

Principal Investigator: Dr. J. J. Craighead
Co-Investigators: Dr. F. C. Craighead Jr.
Joel R. Varney

RECEIVED
NASA STI FACILITY
INPUT BRANCH
SEP 1971

Montana Cooperative Wildlife Research Unit
University of Montana
Missoula, Montana 59801

July 31, 1971

N71-35260	
(ACCESSION NUMBER)	(THRU)
111	G3
(PAGES)	(CODE)
CR-121893	05
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

FACILITY FORM 602

CONTENTS

SUMMARY

The general objectives of the work done under NASA Research Grant NGR 27-002-006 were to improve existing ground radiolocation equipment for use in conjuction with satellite animal tracking experiments, and to investigate various approaches to sensing and telemetering physiological data from instrumented animals. The goal of this work is to develop a strong technology and experience base for future NASA experiments involving the use of satellites in wildlife research programs.

Considerable progress has been made toward these objectives during the contract period. The radiolocation system developed by the investigators for use on elk and grizzly bear was used in the IRLS elk tracking experiment conducted during the spring and summer of 1970, and valuable experience was gained in integrating this equipment with the IRLS collar and in using it to locate the elk both on the ground and from the air to check satellite location data. Techniques were tested for interrogating the IRLS collar from an aircraft which may prove useful in future programs as a supplement to satellite interrogations or in helping to locate an animal with a malfunctioning collar. An improved directional antenna and location technique were developed which facilitate location of instrumented animals by aircraft.

Physiological instrumentation work was directed toward experiments with black bears in their winter dens. This approach allows our efforts to be concentrated on equipment and instrumentation

techniques without requiring the expenditure of a large number of man-hours locating and following instrumented animals. At the same time it is providing useful information on a little-studied aspect of the life history of wild bears.

Details of various aspects of the work completed during the contract period are discussed in the following sections.

INTEGRATION OF GROUND TRACKING TRANSMITTER WITH IRLS ELK COLLAR

A ground tracking transmitter was used with the IRLS elk collar to permit precise location of the animal by observers when desired. Information on movements was obtained in this way for comparison with satellite location data. It also served as a backup method of locating the animal to recover the satellite instrument package in case of an equipment failure. A brief description of the ground tracking system is given in Appendix A, and a summary of the IRLS elk tracking experiment in appendix B.

Ground tracking systems will be desirable supplements to satellite location equipment for the immediate future if animal position errors on the order of a mile or less are necessary or if visual observations of the animal are desired, and will be useful in the field phases of future satellite equipment development programs. Accordingly, the methods used to integrate the ground tracking transmitter with the IRLS elk collar should be of interest.

Collar for 1970 IRLS Elk Tracking Experiment

In the first tracking experiment the IRLS collar, fabricated by Radiation, Inc., was made of fiberglass. The ground tracking transmitter loop antenna was wrapped around the outside of the collar near the front edge. This technique provided satisfactory radiation,,although cables for the 400 MHz antenna and light sensors running parallel to the 32 MHz antenna caused some losses because of induced currents. Considerable improvement in radiated signal strength from the initial configuration was observed when a grounding strap was connected from the 400 MHz antenna - support structure to the frame of one solar cell panel. The position of the strap for maximum radiation was experimentally determined and it was permanently attached to the collar before placement on the elk.

Mockup Collars for 1971 IRLS Elk Tracking Experiment

Two mock-up fiberglass collars were constructed in March, 1971, in preparation for the planned second elk-tracking experiment. These collars were fitted with ground-tracking transmitters to permit easy location and recapture of the animals to be fitted with the redesigned IRLS collar. Photographs of the collar are shown in figure 1. The location and attachment of the transmitter and antenna are similar to that used in the Radiation collar. An

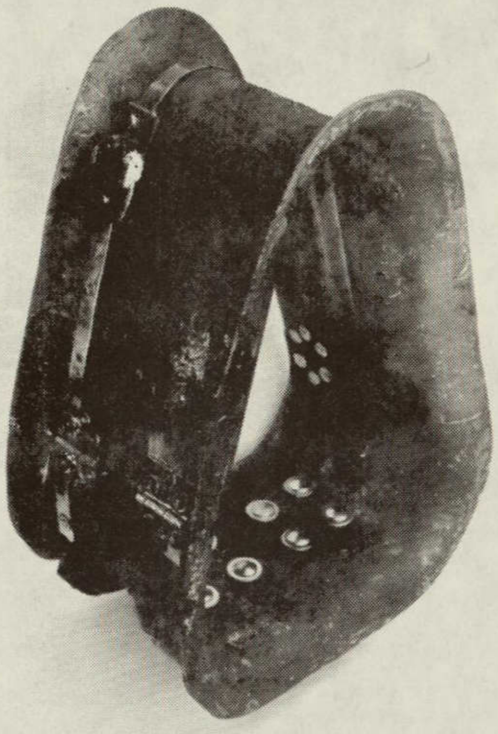
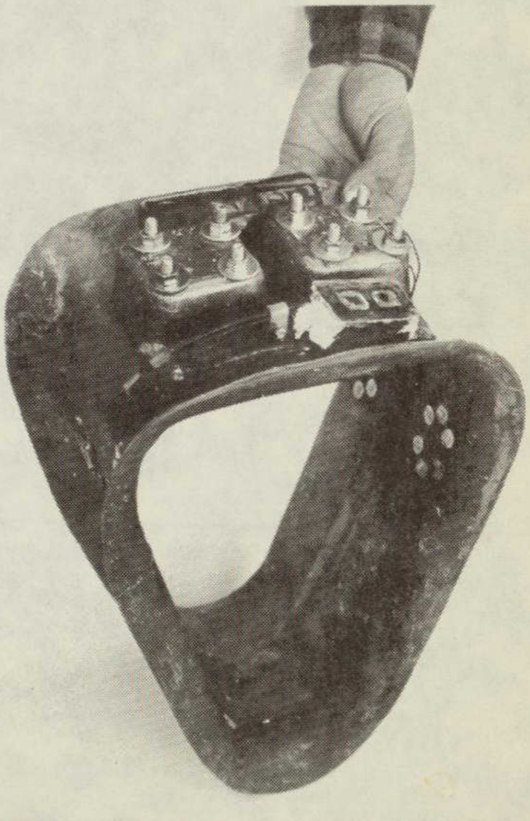


Figure 1:

Mock-up elk collar before final fiberglass coating was applied, showing placement of ground tracking transmitter and antenna. The collars were weighted to match the GSFC redesigned collar.



improved method of installing the collar was devised; this consisted of fabricating it in two halves connected with hinges secured by cotter pins. Removal of four pins allowed the collar halves to be separated and placed on the animal, after which the pins were reinserted. The electrical connections of the tuned loop antenna were part of this arrangement, eliminating the need for separate screw connections as in the Radiation collar and reducing the installation time required.

Collar for 1971 IRLS Elk Tracking Experiment

The reduced-weight IRLS collar designed at GSFC for the second elk-tracking experiment was constructed of metal rather than fiberglass, so it was necessary to devise a different antenna arrangement than was used in the earlier collars.

A diagram of the GSFC collar design is shown in figure 2. It consists of a sealed aluminum box containing batteries and electronics, attached to the elk's neck by an inverted U-shaped aluminum tube framework. The tube framework is insulated from the electronics box by bakelite spacers to prevent the collar assembly from acting like a shorted-turn loop and reducing radiation from the ground tracking loop antenna. The ground tracking equipment was to be installed in the collar at the University of Montana just prior to placing the instrument package on the elk.

The method developed for installing the ground tracking transmitter on the redesigned collar is shown in figure 3. Rather than placing a separate loop around the periphery of the collar, it was decided to use the collar structure itself as the antenna. One of the bakelite insulating blocks is replaced with a metal block, and loading capacity is added across the other insulating block to resonate the structure at 32 MHz. The transmitter is mounted on one side of the electronics package as shown in the diagram and the connection between the transmitter output and the collar structure is made through a 6-inch coaxial cable spaced about 1 inch from the frame with a bakelite standoff. This connection serves as an inductive tap or gamma match, and its length is adjusted to provide the correct impedance matching between the transmitter and the antenna formed by the collar. This technique has been used in the ground tracking transmitters used on bear and elk with good results.

Breadboard tests of this approach showed that the inductance of the collar structure is a function of both surface area and diameter, so that the amount of loading capacity necessary to resonate the structure is best determined experimentally on the final collar. Since the second experiment scheduled for April 1971 was cancelled before the collar was shipped to the University of Montana, there has not been an opportunity to make the transmitter installation and measure the radiation properties of this antenna. This could be done in the future if it appears that the instrument package will be used for any kind of animal tracking experiments.

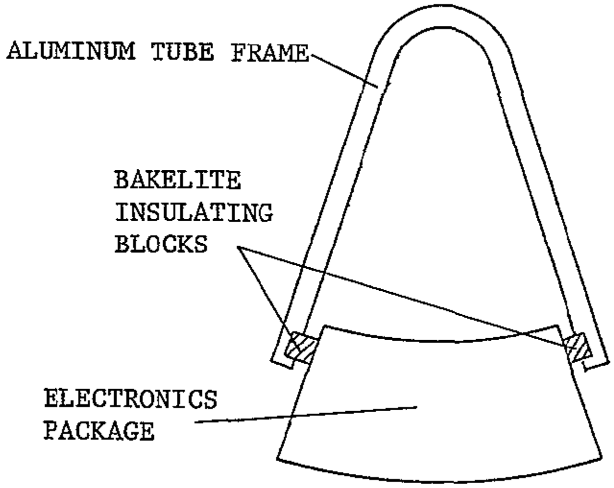


Figure 2: Construction of GSFC elk collar

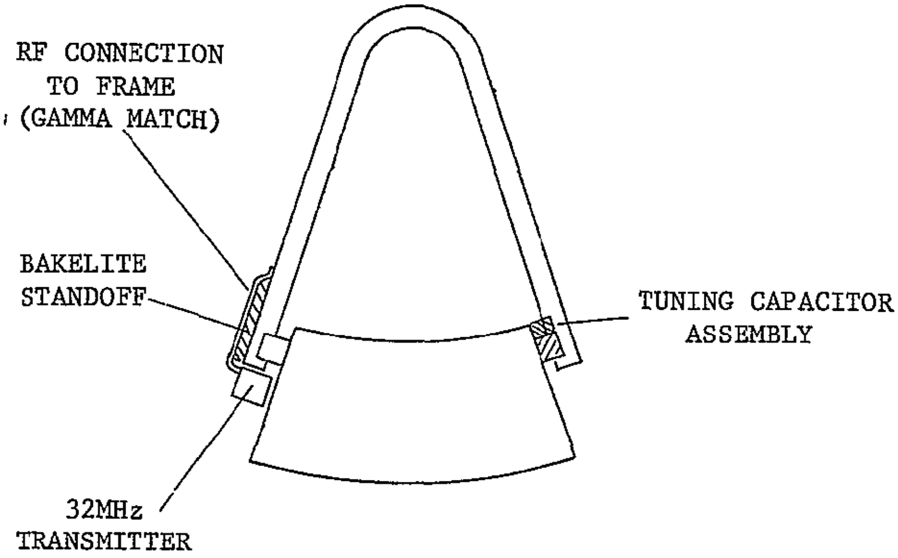


Figure 3: Attachment of ground tracking transmitter to collar

LOCATION OF IRLS-INSTRUMENTED ELK FROM AIRCRAFT

As part of the support activities for the first IRLS elk-tracking experiment, procedures were worked out for interrogating the collar from an aircraft after satellite contact had been lost. Although no responses were received from the collar during flights in August and September, 1970, because it was inoperative (later examination of the recovered collar showed that one timer had stopped), the equipment and procedures used are described below since they could be used in future experiments as an alternative means of locating instrumented animals or instrument packages. With appropriate modifications in the receiving equipment, range and telemetry data could also be collected and stored by aircraft as well as by the satellite.

Equipment

A block diagram and photograph of the equipment used in the aircraft are shown in figures 4 and 5. The 466 MHz FM transmitter, diplexer, and 401.5 MHz receiver are NASA engineering models of the equipment aboard the Nimbus satellites. A BIP test set provides transmitter modulation and digital processing of the receiver output. It generates the desired address code for platform interrogation, recognizes a platform response, and displays a panel light when a platform response is received. An interface control box provided power connections, on/off control of the

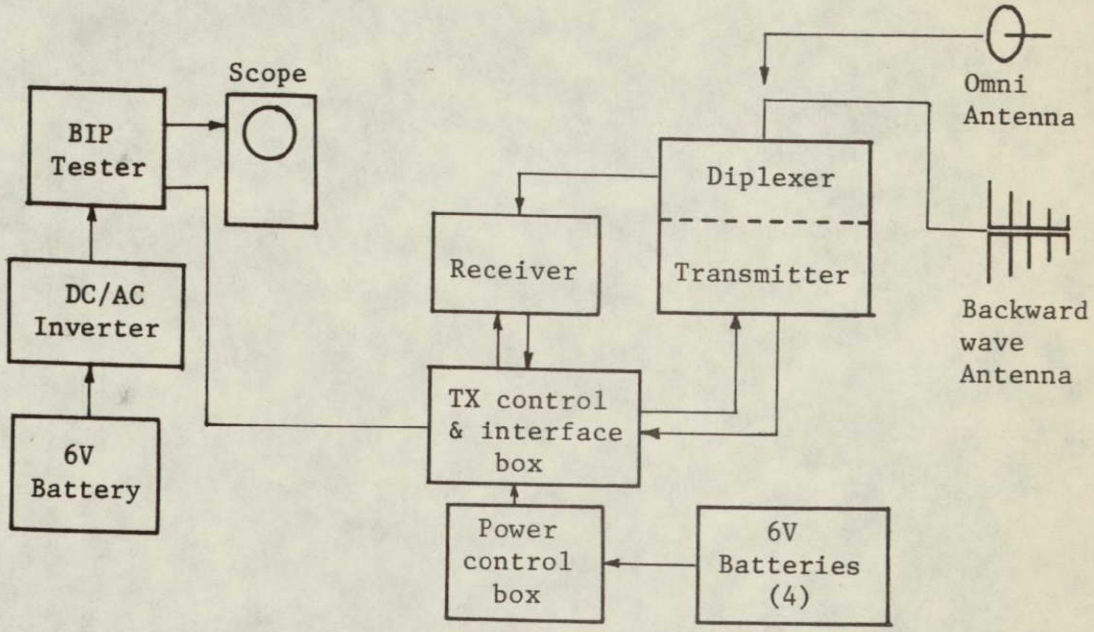


Figure 4: IRLS collar interrogation equipment block diagram

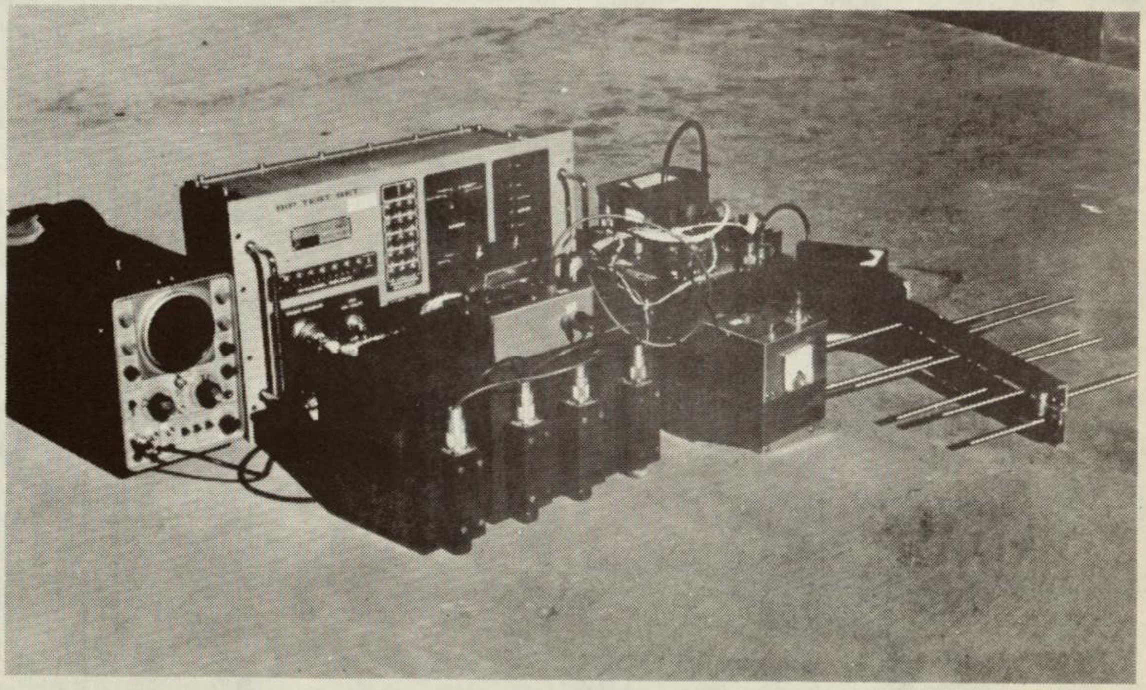


Figure 5: Interrogation equipment

NOT REPRODUCIBLE

transmitter, and a video data driving circuit for the transmitter.

Power for the BIP test set was furnished by a Heathkit MP-10 DC/AC inverter which was powered by a Sonotone BB-429/U 6 volt nickel-cadmium battery. A separate battery was used to prevent possible converter interference with transmitter or receiver operation. Power for the transmitter and receiver was provided by four 6 volt BB-429/U batteries connected in series. A power control box contained meters for battery voltage and current along with an on/off switch.

Provision was made for operation with either of two antennas. A quarter wave whip antenna with a half wave diameter ground plane was used for omnidirectional coverage. A log-periodic backward wave antenna (Prodelin 46-570) was used for direction finding. This antenna gives a 60° by 106° pattern with 6 dB gain, and input VSWR below 1.5 over the frequency range between 400 and 470 MHz. The antennas were connected to the transmitter diplexer by 12 foot RG-58 cables with approximately 1 dB transmission loss.

The receiver video waveform was monitored with a Tektronix 321A portable oscilloscope. This permitted detection of signals below the BIP test set phase lock threshold.

Range Tests

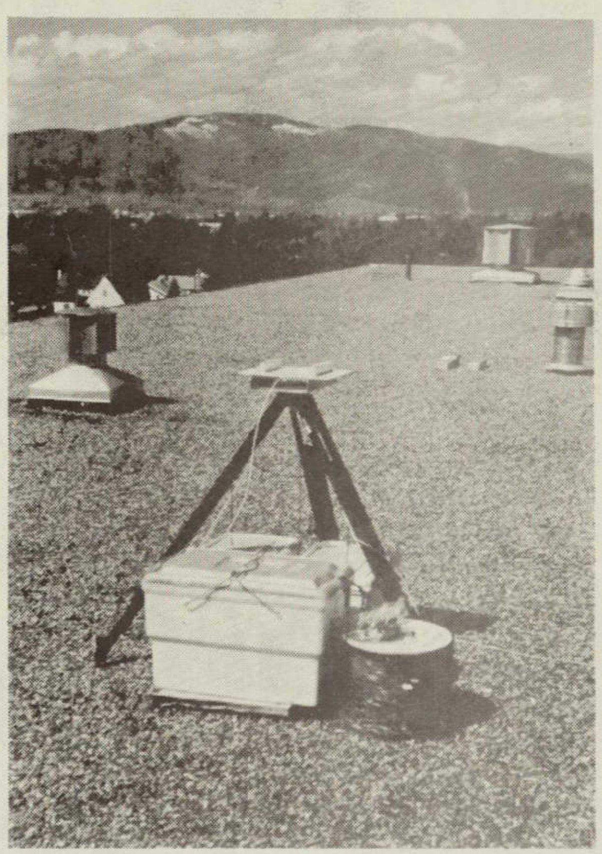
To test the range and operation of the equipment, it was taken by automobile to the Blue Mountain lookout near Missoula and used to interrogate an IRLS platform on the roof of the Health

Science building on the University campus (shown in figure 6). Tests were made at various ranges enroute.

A circularly-polarized fin antenna developed by GSFC for possible use on the elk collar was used on the rooftop station. The direction of arrival of the signal from the portable equipment was nearly 90° from the antenna north-south axis and at elevation angles between 0° and 5°. The fin antenna gain is relatively low in this direction and should be similar to that of the elk collar antenna in the inverted position (as was the case with the collar when Monique was last seen).

A GO indication (BIP test set phase lock) was obtained with both the whip and backward wave antennas at ranges of 2.5 and 5.5 miles. At 10 miles the signal was too weak to give a GO light on the test set but was clearly visible on the receiver video output. The rooftop platform was turned on by the interrogation signal and the received video signal from the platform could be seen for about 1 second after turnoff of the portable transmitter. The usable range of the system was accordingly judged to be at least 10 miles.

The direction of arrival of the platform response could be determined by turning the log-periodic antenna while observing the video waveform on the oscilloscope; signal noise increased as the antenna was moved away from the direction of the platform.



NOT REPRODUCIBLE

Figure 6:

IRLS platform used for range tests. The fin antenna is mounted on a tripod, with batteries and platform electronics in styrofoam boxes. Interrogations were made from Blue Mountain in the background.

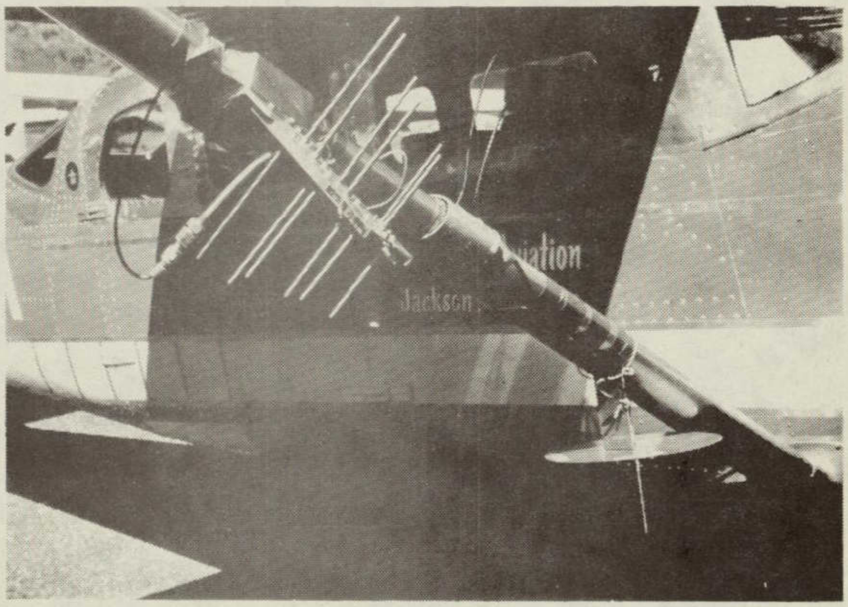


Figure 7: Log periodic antenna (left) and omnidirectional antenna (right) attached to aircraft wing strut for search flights

Flight Search Methods

For the search flights made in the vicinity of the National Elk Refuge, both the whip and directional backward wave antenna were attached to the right-hand wing strut of a Cessna 206, with the directional antenna pointed about 30° below horizontal and 30° to the right of the line of flight. The whip antenna was vertical. The directional antenna was used for nearly all interrogations because of its reasonably broad pattern and higher gain. The antenna arrangement is shown in figure 7.

Considerable ground area could be searched in a short time with this technique. Using conservative system range estimates of 5 miles for a GO indication on the BIP test set and 10 miles for a scope indication, the area shown in figure 8 was covered during a 40 minute flight at an altitude of 5000 feet above ground level. Had the collar been operating, a response would have been received if the animal was within the cross-hatched area (about 650 square miles).

Aircraft flights would be a valuable supplement to satellite interrogations if it were desirable to obtain locations or data in the period between satellite overpasses. In addition, a damaged but still operative collar could be located in this way; the RF path loss between the Nimbus satellite and the earth's surface is about 144 dB, while it is only 87 dB from an aircraft at an altitude of 5000 ft. The 57 dB increase in link margin with the aircraft

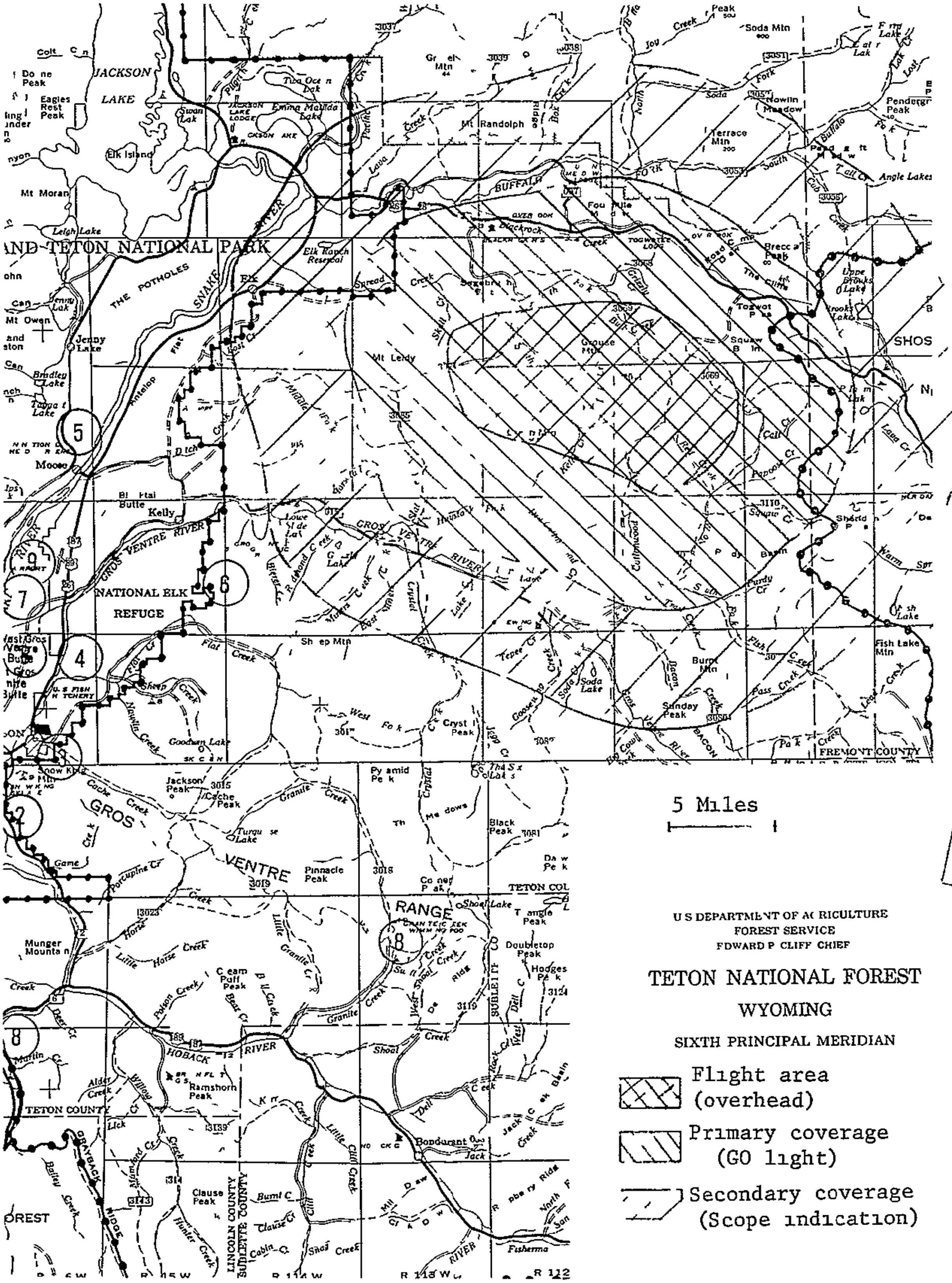


Figure 8· Area searched during a 40 minute flight at 5000 feet altitude would permit location of a collar with a badly damaged antenna or transmitter that could no longer be reached by the satellite.

DIRECTIONAL ANTENNA FOR ANIMAL LOCATION FROM AIRCRAFT

One of the proposed research objectives was to investigate improved directional antennas for use on small aircraft to locate instrumented animals. A homing-type antenna was developed and tested with excellent results; it is expected to be very useful in locating animals carrying radio collars.

In the IRLS elk tracking experiment, an aircraft was used to locate the animal when she had moved a long distance from the last observed position. The signal from the 32 MHz ground tracking transmitter was picked up with an 11" diameter tuned loop antenna attached to the wing strut of the plane (usually a Cessna 150). Although signals could be received from the collar under favorable conditions at ranges up to 20 miles at altitudes between 1000 and 3000 feet above ground level, the relatively low gain of the antenna is a disadvantage at times. A second disadvantage is the necessity of turning the aircraft in order to use the loop nulls and maxima to determine the directional of signal.

As the second satellite elk tracking experiment planned for the summer of 1971 was cancelled, we decided to test an improved antenna concept by designing a system for operation at 150 MHz rather 32 MHz. This allowed us to take advantage of a study already in progress at the University of Montana in which seven elk have been instrumented with radio collars. In this way, the performance of the antenna could be tested by actual field use and its effectiveness in locating animals under various conditions and in different types of terrain could be evaluated.

Antenna Description and Construction

The antenna system developed is similar to one that has been used for aircraft homing applications in the past, simplified and adapted for use with pulsed signals. It is a two-element driven array consisting of two 1/4-wavelength grounded whip antennas spaced 1/4 wavelength apart attached to the underside of the aircraft fuselage. A 1/4 wavelength delay line in series with one of the antennas causes a 90° phase shift in one signal before it is combined with the signal from the other antenna. The result is a cardioid-shaped pattern with a null on one side and a maximum on the other. A diagram of the pattern is shown in figure 9. A switch is arranged so that the delay line can be connected to one antenna or the other, which reverses the direction of maximum sensitivity. With the antennas mounted side by side on the aircraft, the patterns shown in figure 10 are obtained.

The antenna mounting and switch connections are shown in figure 11. The antenna length and spacing for the 150 MHz operating frequency is 50 cm (19.5 inches). It can be adapted for use at

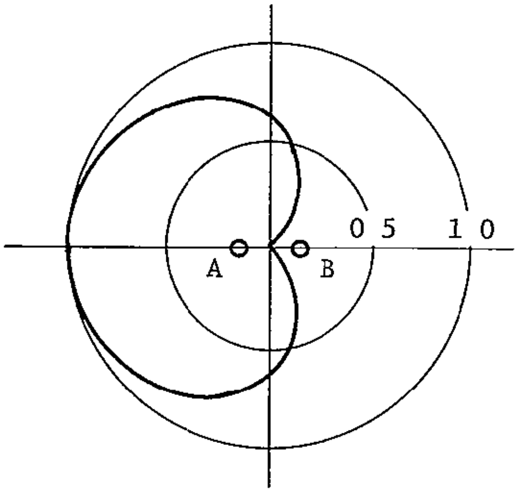


Figure 9: Antenna pattern for two dipoles spaced 1/4 wavelength apart and driven 90° out of phase (A delayed)

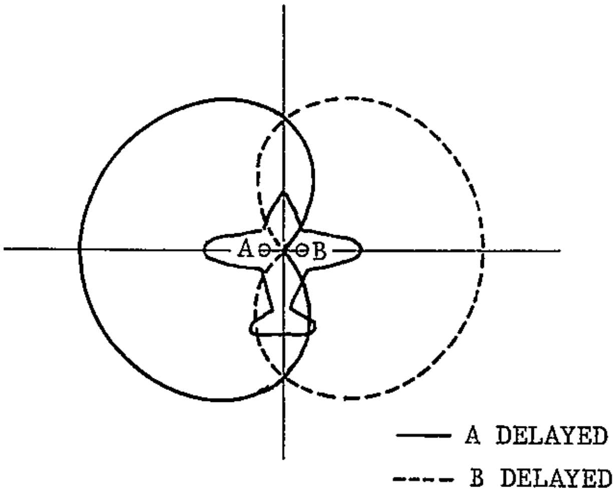


Figure 10: Antenna patterns for dipoles mounted on the aircraft pitch axis with delay line switched from one antenna to the other

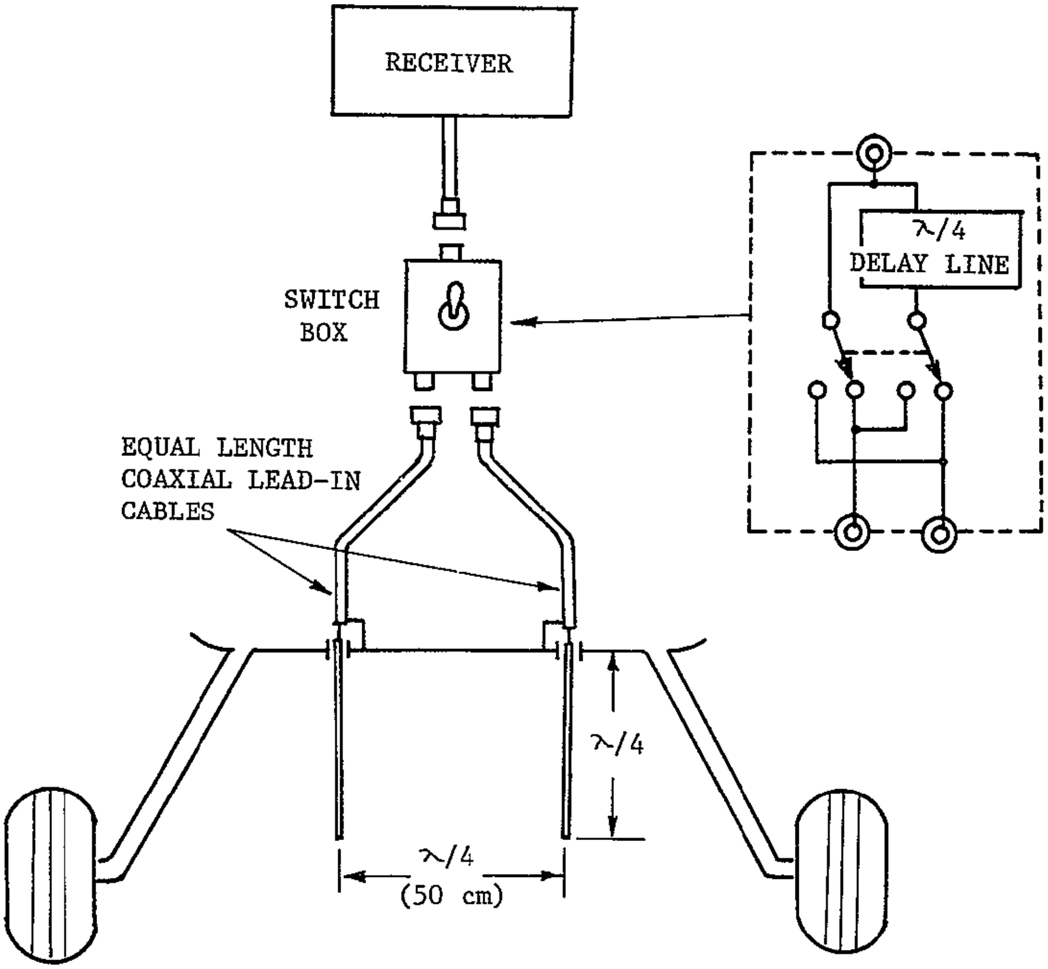


Figure 11: Diagram of antenna mounting and connections

other frequencies by appropriate scaling of the antenna dimensions and spacing. Mounting the antennas under the belly of the aircraft, as shown in figure 12, would be suitable for frequencies around 100 MHz or higher. For lower frequency systems such as the 32 MHz system used in the IRLS elk tracking experiment, inductively-loaded whips mounted on the wing struts would probably be the best configuration.

The antennas can be mounted on brackets for temporary attachment to various aircraft, as shown in figure 13. This is preferable to permanent mounting if rented aircraft are being used, or if tracking operations are conducted from different aircraft from time to time.

Photographs of the switch box are shown in figures 14 and 15. A miniature DPDT toggle switch is wired as a reversing switch to connect the delay line in either the right or left antenna path. The delay line consists of 36 cm (14 in) of RG-174/U miniature 50 ohm coaxial cable coiled inside the box. As in the case of the antennas, the delay line length would be changed if a different operating frequency was desired or if a cable with a different velocity factor were used.

Performance tests

Performance measurements on the aircraft under actual operating conditions were not feasible, but patterns measured with

Figure 12: Antenna system installed in the landing gear access holes of a Cessna 185

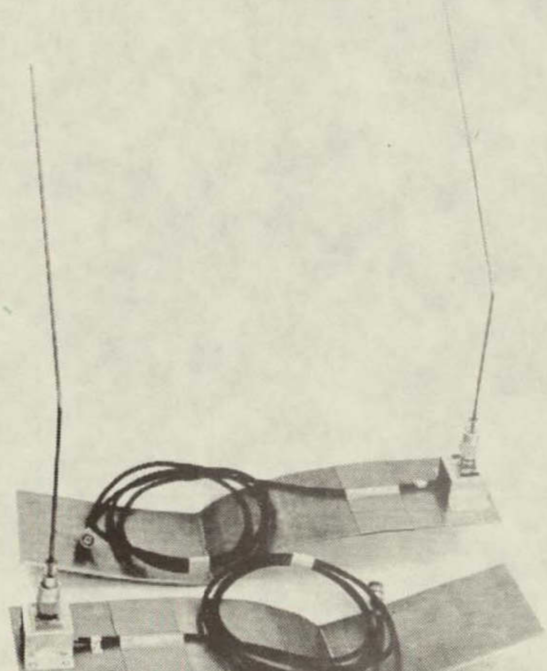


Figure 13:

Antennas mounted on brackets to permit external attachment to the landing gear of a Cessna 182. The antennas may be bent slightly as shown to provide sufficient ground clearance when mounted without major effect on the antenna pattern.

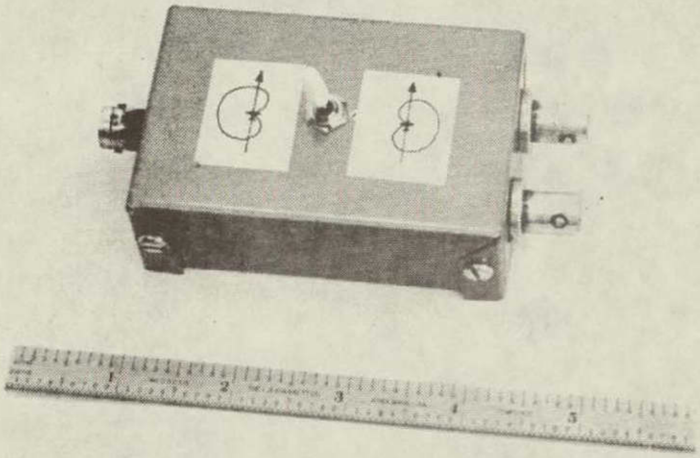


Figure 14: Antenna direction switch. A diagram of the antenna pattern is placed by each switch position to aid the observer when tracking an animal.

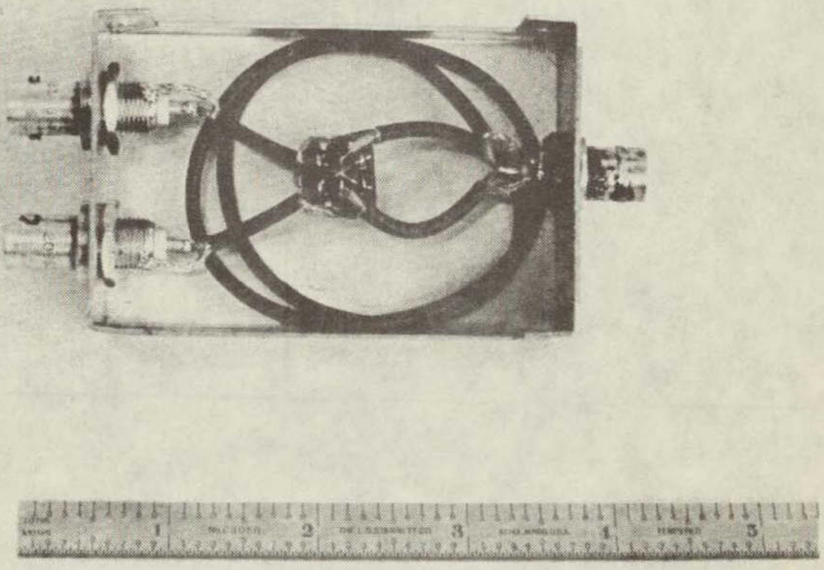


Figure 15: Inside of switch box, showing the placement of the 1/4 wavelength delay line and coaxial cable connections between BNC receptacles and switch.

the antennas mounted on a 3 x 5 foot ground plane to simulate the aircraft skin are shown in figure 16. Reasonably good symmetry was obtained, with equal signal crossover points between right and left patterns occurring within a few degrees of the 0° and 180° axes. The pattern null in each case was 12 dB below the maximum. The slight rotation of the pattern maximums and nulls from the 0°, and 90°, 180°, and 270° axes was probably caused by signal reflections from a nearby fence during the test and not present when the antennas are mounted on the aircraft.

Use and Results

In use, the antenna switch is moved from one position to the other and the received signal strength in each position is noted, either by volume or by use of the receiver signal strength meter. In this way it can be quickly determined if the animal is to the right or the left of the aircraft line of flight. The aircraft can then be turned in the indicated direction until the signal levels are equal in both switch positions, indicating that the instrumented animal is on the line of flight, and flown directly to the animal's location. A pattern null exists directly underneath the antenna which causes a momentary reduction in signal level when the aircraft passes over the animal. After this occurs, the aircraft can then circle, with the antenna pattern being switched from side to side as necessary, while a visual search is made for the animal.

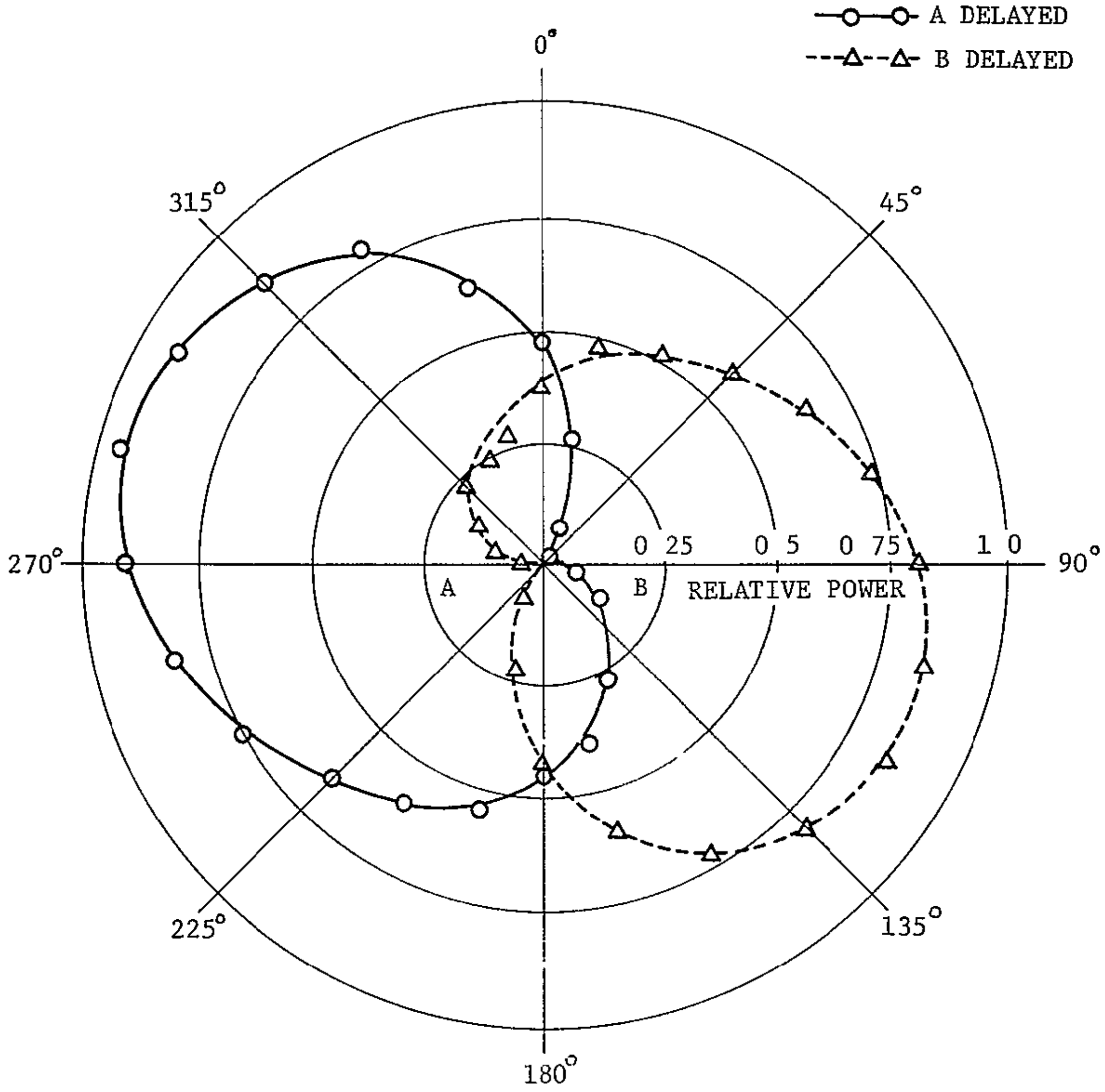


Figure 16 Measured antenna patterns

The antenna system has been in use for two months and has proved to be very satisfactory for locating instrumented elk in all kinds of terrain. It is particularly effective in rough or mountainous country where multipath and shielding effects cause large variations in signal strength. With the fixed loop or yagi antennas used previously, changes in signal level from the directional antenna as the aircraft was turned were obscured by multipath variations as the aircraft flew by the animal, making accurate location very difficult. With the electrically switched pattern, the direction of maximum sensitivity can be shifted instantaneously, eliminating this problem. It is usually possible to locate all seven instrumented elk, which are scattered over an area of about 140 square miles, to within 1/4 mile of their actual position in a one to two hour flight. Usually several animals are sighted visually, with as many as 6 of the 7 having been seen during a flight.

BLACK BEAR HIBERNATION STUDIES

Tenative plans have been made to do further studies of black bear hibernation mechanisms and behavior during the winters of 1971-72 and 1972-73, using either the Nimbus 4 IRLS or ERTS-A Data Collection Systems. The general procedure will be similar to that used in the first experiment (described in appendix C), but improved and additional sensors and techniques will be used to obtain more sophisticated information about the bear's condition and behavior than previously. Preparatory work that has been completed for these experiments is described below, and includes preparations for experimental surgical implants on a captive hibernating bear, a survey of implantable physiological transmitters, preliminary work on improved environmental sensors, investigation of several den sites, and a brief survey of data storage methods.

Our initial plans were to develop prototype receiving and conversion equipment so that temperature and heart rate data could be obtained from an implant in an elk instrumented with the redesigned IRLS collar. However, in view of the advisability of extensive pre-testing of the equipment and surgical techniques, and the cancellation of the satellite tracking experiment scheduled for this spring, the effort was shifted to preparations for obtaining the same data from the black bear. The equipment and procedures will be quite similar for either case, and can easily be adapted to future experiments involving tracking and telemetering physiological data from free-roaming animals by satellite.

A field experiment will be attempted during the winter of 1971-72 if the tests on the captive bear are completed in time and approval is obtained from NASA to use the IRLS system. A proposal has been submitted to NASA (applicability of the ERTS DCP to Wildlife Research, 27-002-007) regarding use of the ERTS Data Collection System for an experiment during the winter of 1972-73.

The use of satellite equipment for these experiments is desirable but not essential. If such experiments do not fit in with presently evolving NASA plans regarding the use of satellites in animal tracking and physiology research until a later date, they will be conducted with on-site telemetry and recording equipment. In this way, the necessary development and testing of equipment and techniques can proceed in an orderly fashion preparatory to their use in connection with satellite experiments.

Preparation for Experiments with Captive Bears

Temperature measurements obtained in the previous den-monitoring experiment were from a rectally-inserted temperature-sensitive transmitter. This method does not require surgery on the animal, but provides less accurate data than an implant since the transmitter is subject to movement or expulsion. For heart rate measurements, a surgical implant would help to avoid the electrode attachment and movement problems that usually occur with an externally-attached instrument package.

If surgical implant techniques are used, it will be advisable to test the implant procedure before attempting field surgery under winter conditions on a hibernating bear. We plan, therefore, to conduct preparatory surgical experiments and equipment tests on a captive bear at the University of Montana. We are presently investigating the feasibility of setting up an artificial den for these experiments in an unused cell block in a University-owned building at Fort Missoula.

Survey of Implantable Physiological Transmitters

A survey was made of implantable temperature and EKG transmitters that have been developed by various investigators and private companies to determine whether one of them would be suitable for use in our experiments.

Temperature-sensing transmitters are comparatively simple to construct, so it is probable that we will build units at the University of Montana rather than try to obtain them elsewhere. This will allow some flexibility in choice of modulation methods to insure compatibility with the EKG transmitter selected. If the Franklin Institute transmitter is used (see discussion below) a separate temperature unit will not be necessary.

A summary of the characteristics of the EKG transmitters that were investigated is given in Table 1. These include both commercially-available units and non-commercial transmitters that could be used by making suitable arrangements with the investigators who developed them. Other non-commercial transmitter designs that have been reported in the literature (see references) were considered less suitable for various reasons and are not included in Table 1.

The unit made by Franklin Institute appears to be the best

TABLE 1 EKG TRANSMITTER COMPARISON

Manufacturer	Model	Frequency	Modulation	DC Power	Battery Type	Operating Life	Weight (incl. bat)
Belair Laboratories	M5	90-95 MHz	FM	450uA @ 1.4V	RM 625	23 days	5 gr
E&M Instrument Col	FM-1100-EP	88-108	FM	350uA @ 2 8V	RM312(2)	4 days	8 gr
EKEG Electronics Ltd.	F681	88-108	FM	3mA @ 5.6V	RM312(4)	12 hrs	32 g
Bio-Sentry Telemetry Inc	TX 201 VCO 1100 AMP 2100	215-360	FM/FM	3mA @ 8.4V	RM312(6)	12 hrs	34 g
American Electronics Laboratories	3100T	88-108	FM/FM	2mA @ 1.3V	RM625	7 days	20 g
Franklin Institute (Goodman)(1)	-	88-108	PFM			1.5 yrs	6 gr
University of Iowa (Folk)	-	200-500kHz	FM			6 mos 2 yrs	7 gr 40 gr
NASA, Ames Research Center (Fryer)	-	88-108MHz	FM/FM	0.8 mA @ 1 4 V(2) 32uA @ 1 4V(3)	RM312	45 hrs(2) 48 days(3)	2 g

Notes

(1) transmits both temperature and EKG data

(2) continuous mode

(3) pulsed mode - reduced range

choice for our purposes at present. It transmits both EKG and temperature information, is quite small, and has long battery life. The pulse frequency modulation technique used is compatible with low power receiving and recording equipment that would be necessary for long periods of unattended operation at the den.

Improved Environmental Sensors

Improved instrumentation is being developed for the den to enable us to learn more about the mechanisms of hibernation and heat conservation. In addition to the light and temperature measurements made in the first experiment, sensors are being investigated that would allow measurement of relative humidity, thermal radiation, thermal flux, and movements. Sensors for the humidity and thermal parameters have been developed and are commercially available. Development of interface circuitry for these sensors is in progress.

Several possible methods of determining the bear's movements in or around the den are being investigated. One will be selected for the experiment this winter after further study and, if necessary, breadboard tests. The approaches under consideration include (1) recording the strength of the signal received from the implanted temperature or EKG transmitters, (2) a grid of temperature sensors on the floor of the den, (3) a sensitive seismic vibration detector similar to those used by the military as intrusion alarms, (4) a wire loop placed on the den floor and excited with a 20 KHz signal which shifts frequency slightly as movements of the bear's body cause inductive changes, or (5) a magnetic field sensing arrangement which would respond to changes in position of a small magnet attached to the bear.

Den Location

Several reported black bear den locations near Libby and Perma, Montana, were examined during January and February. The location and condition of the dens were noted. While the probable method of selecting the den for an experiment this fall will be to instrument one or two bears with radio collars and follow them until they hibernate, it will be useful to have several alternative den sites in case any difficulties are encountered in locating the instrumented bears or in the event that they hibernate in very inaccessible areas.

Data Storage Methods

To be of maximum use, physiological data should be collected from instrumented animals at fairly short intervals (ranging from several times a minute to once an hour). If such data is to be collected by satellite, either a synchronous orbit must be used to permit real-time readout, or, in the case of polar orbit satellites such as Nimbus or ERTS, some methods of data storage must be provided for the interval between interrogations.

A brief survey was conducted of various methods of data storage that might be satisfactory for this application. These included magnetic tape recording, core memories, and various semiconductor memories including bipolar transistor, MOS, complementary MOS, and Ovonic types.

At present it appears that CMOS semiconductor memories would best meet our requirements, which include high-speed readout capability, low power consumption, low to medium cost, and moderate data capacity.

The logic design of a data storage system will depend on the satellite system with which it is intended to be used. Since present plans involving use of satellites in our experiments are fairly tentative and in view of the large design effort that will be required to breadboard a system, we have deferred further work in this direction until NASA's animal tracking program plans have developed further. Study of CMOS memories will continue and portions of a data storage system may be breadboarded to permit evaluation of power consumption and performance characteristics.

REFERENCES

The following reports and articles describe various types of telemetry systems for monitoring physiological parameters. It was evident from the titles of some references that the systems were not suitable for our use; these were not checked. The remaining reports were examined and the equipment described was found to be less desirable than that listed in Table 1, for various reasons. Some features of several systems were applicable to our situation and may be incorporated in our physiological telemetry equipment, depending on the amount of existing equipment used and other system tradeoffs.

Adams, R.M., G. Fromme, D. Dizon, G. Anstadt. 1963. A microwatt VHF telemetry system for implantation in small animals. Proc. 1963 Nat. Telem. Conf., session 5-2.

Almond, J. A. 1965. Personal telemetry transmitter system. AMRL-TR-65-87.

Bligh, J., D. L. Ingram, R. D. Keynes, S. G. Robinson. 1965. The deep body temperature of an unrestrained Welsh sheep recorded by radiotelemetric technique during a 12-month period. J. Physiol. 176(1):136-144.

Buchanan, H., W. F. Moore, C. R. Richter. 1969. Recoverable temperature-sensing implant. SAM-TR-69-69 (AD 700 737).

_______ et al, 1967. Temperature-sensing telemetry system for unrestrained Rhesus mondeys (Macaca mulatta). SAM TR-6763 (AD 659 365).

Clagg, B. R. et al. 1966. Studies of circadian cycles in human subjects during prolonged isolation in a constant environment using eight-channel telemetry systems. NASA-CR-74032 (N68-19137).

Cooper, W. N. 1962. Internal Biological Telemetry System - Feasibility study, flight test phase. SSD-TR-62-43.

Downhower, J. F., F. D. Pauley. 1970. Automated recordings of body temperature from free-ranging yellow-bellied marmots. J. Wildl. Mgmt. 34(3):639-641.

Frank, T. H. 1968. Telemetering the electrocardiogram of free swimming Salmo irideus. IEEE Trans. Bio-Med. Engrg. 15(2):11-114.

Holcomb, W. G., P. J. Rasch. 1969. Development of the NMFRL telemetry system, second report. (AD 682 690).

_______ and _______. 1970. Evaluation of a prototype unit for telemetry of rectal temperatures. NMFRL-VOL-XX/NO-5 (AD 706 329).

Kavanagh, D. A. 1963. Development of miniature telemetry system. SAM-TDR-63-80.

Kavanagh, L. 1968. A subminiature crystal-controlled biological transmitter. World Med. Electr. 6:108-111.

Kezdi, P., W. S. Naylor. 1965. Telemetry system to transmit baroreceptor nerve action potentials. Am. J. Med. Electr. 4(4): 153-155.

Ko, W. H., W. Thompson, E. Yon. 1963. Tunnel diode FM transmitter for medical research and laboratory telemetering. Med. Electr. Bio Engrg. 1:363-369.

________ et al. 1967, 1968. Investigation of implantable multichannel biotelemetry systems, Semiannual reports. NASA-CR-96891, NASA-CR-91524, NASA-CR-97832.

________et al, 1969. System design and fabrication technique for multi-channel, physiologically implantable telemetering systems for biological measurements, semiannual report. NASA-CR-100920.

Kuck, Liebman, Kussick, 1963. A miniature transmitter for telemetering muscle potentials. IEEE Trans Bio-Med. Electr. 10:117-119.

Lonsdale, E. M., J. W. Steadman, W. L. Pancoe. 1966. A telemetering system for securing data on the motility of internal organs. IEE Trans Bio-Med Engrg. 13:153-159.

McElligott, J. G. et al. 1968. A miniaturized telemetry device for the transmission of the electrical activity of single nerve cells in the brain. NASA-CR-101403 (N69-27913).

McGinnis, S. M., V. A. Finch, A. M. Harthoorn. 1970. A radiotelemetry technique for monitoring temperature from unrestrained ungulates. J. Wildl. Mgmt. 34(4):921-925.

Mackay, R. S. 1964. Deep body temperature of untethered dolphin recorded by ingested radio transmitter. Science 144(3620): 864-866.

Marko, A., M. A. McLennan, E. C. Correll. 1963. Research and development on pulse-modulated personal telemetry systems. AMRL-TDR-63-96.

_______, R. H. Murray, A. T. Kissen, D. M. McGuire, 1967. A new versatile miniature multichannel personal telemetry system for medical research. AMRL-TR-67.

Murray, R. H., A. Marko, A. Kissen, D. McGuire, 1968. A new miniaturized multichannel personal radiotelemetry system. J. Appl. Physio. 24:588-592.

Pauley, J. D., H. W. Shirer, D. D. Pippitt. 1968. A simple pulsed transmitter for telemetering body temperature from free ranging animals. IEEE 1968 Nat. Telem. Conf. Record, p386-390.

Robrock, R. B., W. H. Ko. 1967. A six channel physiological telemetering system. IEEE Trans. Bio-Med. Engrg. 14:40-46.

Rokushima, H. 1969. A multi-channel PWM/FM radio-telemetry system for EEG. Proc. 22nd Ann. Conf. on Engineering in Med. and Biol.

Roy, Hart. 1966. A multichannel transmitter for the physiological study of birds in flight. Med. Biol. Engrg. 4:457-466.

________ and ________. 1963. Transmitter for telemetry of biological data from birds in flight. IEEE Trans. Bio-Med. Electr. 10:114-116.

Simons, Prather. 1964. A personalized radio telemetry system for monitoring central nervous system arousal in aerospace flight. IEEE Trans. Bio-Med. Engrg. 11:40-51.

Skutt, H. R., R. G. Beschele, D. G. Moulton, W. P. Koella,. 1967. New subminiature amplifier-transmitters for telemetering biopotentials. Electroenceph. Clin. Neurophysiol. 22:275-277.

______, R. B. Fell, R. Kertzer. 1970. A multi-channel telemetry system for use in exercise physiology. IEEE Trans. Bio-Med. Engrg. 17:339-348.

Slater, A., S. Bellet, D. G. Kilpatrick. 1969. Instrumentation for IEEE Trans. Bio-Med. Engrg. 16(2):

Stattelman, Buck. 1965. A transmitter for telemetering electrophysiological data. Proc. Soc. Exp. Biol. Med. 119:352-256.

Trummer, J. R., W. N. Reining. 1969. A four channel telemetry system for intensive care. Proc. 22nd Ann. Conf. on Engineering in Med. and Biol.

Watson, N. W., D. L. Franklin, R. VanCitters. 1968. Back pack for free ranging primates. J. Appl. Physiol. 24:252-253.

Williams, J. M., J.M., J. R. Urbach, J. P. Berneski. 1967. Telemetric monitoring of fetal and neonatal physiological data. Proc. 1967 Nat. Telem. Conf., p. 157-161.

Young, I. J., W. S. Naylor. 1964. Implanted two-way telemetry in laboratory animals. Am. J. Med. Electron. 3(1):28.

Zweizig, J. R., R. Kado, J. Hanley, W. Adey. 1967. The design and use of an FM/AM radiotelemetry system for multichannel recording of biological data. IEEE Trans. Bio-Med. Engrg. 14:230-238.

Zworykn et al. 1961. The measurement of internal physiological phenomena using passive-type telemetering capsules. IRE Int. Conv. Rec. 9(9):141-144.

Appendix A: Varney, J. R.

A Tracking and Telemetry System for Wildlife Research

IEEE 1971 National Telemetering Conference Record, pp. 247-252.

Appendix B: Craighead, F. C. Jr., J. J. Craighead, C. E. Cote, H. K. Buechner

Satellite Tracking of Elk

Appendix C: Craighead, J. J., F. C. Craighead Jr., J. R. Varney, C. E. Cote

Satellite Monitoring of Black Bear

A TRACKING AND TELEMETRY SYSTEM FOR WILDLIFE RESEARCH

Joel R. Varney

Montana Cooperative Wildlife Research Unit
University of Montana
Missoula, Montana 59801

ABSTRACT

This paper describes radiolocation and telemetry equipment developed for use in studies of elk and grizzly bear during the past nine years. It is representative of equipment presently being used by many engaged in wildlife research. Most of it is relatively simple and straightforward in terms of the present state of the art in aerospace telemetry, but illustrates some of the special requirements and approaches used for equipment of this type. Areas in which more sophisticated techniques might prove useful are pointed out, and the probable direction of future development is discussed.

INTRODUCTION

The radiolocation system was initially developed for use in a study of grizzly bear ecology in Yellowstone National Park conducted by Dr. F.C. Craighead Jr. and Dr. J.J.Craighead. It was necessary to have some means of finding particular animals at will, day or night, whether the bear was in the open or hidden in timber, so that observations of behavior and movements could be made. Attaching a small beacon transmitter to the bear proved to be a practical method of doing this. Once the basic location system had been designed and was in field operation, it became apparent that it could easily be upgraded to permit telemetry of environmental and physiological information from the animal. The equipment has also been used in studies of other animals, including black bear and elk.

LOCATION SYSTEM

The following requirements were established for the location system:

Range:	2 miles minimum 20 miles desirable
Transmitter life:	2 months minimum 1 year desirable
Transmitter weight:	under 5 lbs

The system had to be simple to operate since it would be used by field personnel without previous experience in electronics, and mechanically rugged.

A system using a low power CW transmitter and a narrowband phase lock receiver was considered and rejected on the basis of equipment complexity. After some field experimentation with various types of transmitters and receivers, the approach shown in figure 1 was selected. It consists of a 32 MHz transmitter emitting short 100 mW pulses attached to the animal with a resonant loop antenna collar, and tracked by an AM receiver connected to one of a variety of directional antennas.

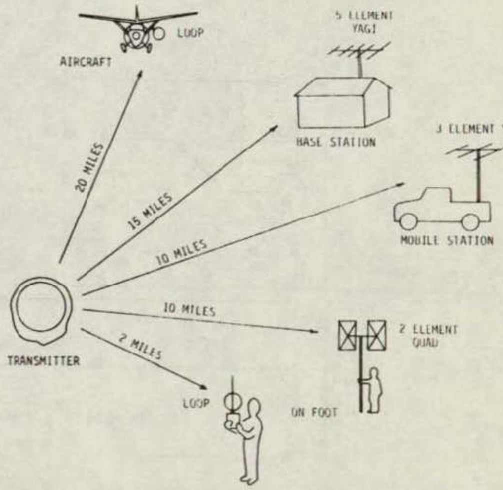


Figure 1: Radiolocation system

In order to maximize transmitter range and life while keeping battery weight to a minimum, a pulsed signal was used. Battery drain was minimized by using a low duty cycle and turning the transmitter off between pulses. The peak power of the pulse was adjusted to give the desired range.

The operating frequency of the system was chosen on the basis of ground propagation characteristics, antenna size constraints, and available frequency allocations. A low frequency was desirable to reduce shielding effects in the mountainous terrain in which the system would be used, while a high frequency would result in smaller and more manageable directional receiving antennas. The 20 to 50 MHz region was chosen as a good compromise, and permission was obtained from the Department of the Interior to use 32 MHz.

Transmitter Design

A circuit diagram of the basic beacon transmitter is shown in figure 2. The oscillator stage Q3 is turned on for 50 ms at 1 second intervals by the astable multivibrator formed by Q1 and Q2. The power amplifier Q4 is a class C stage and draws no current when the oscillator is off, so power consumption is very low between pulses. The transmitter duty cycle is 5%, resulting in an increase of nearly 20 compared to CW operation.

The transmitter will operate for 3 months with a 0.9 lb mercury battery pack. In situations where a longer life is desirable, an additional multivibrator circuit is used to apply DC power to Q1 and Q2 for 10 seconds at 30 second intervals. The result is a series of 10 pulses 1 second apart each 30 seconds, and extends the transmitter life to 9 months.

The construction of the transmitter is shown in figure 3. A cordwood approach with urethane foam encapsulation was used. The multivibrator was fabricated separately to simplify testing and permit installation of a keyer with a desired pulse rate in each transmitter, since the pulse rate is used to identify individual animals.

The transmitter collar assembly is shown in figure 4. The transmitter circuitry is sealed in a 1 x 1 x 2 inch metal can and attached to a brass strap which acts both as a collar and a loop antenna. The loop is resonated at the operating frequency by a tuning capacitor diametrically opposite the transmitter. Impedance matching between transmitter and antenna is provided by an inductive tap 3 inches away from the transmitter case.

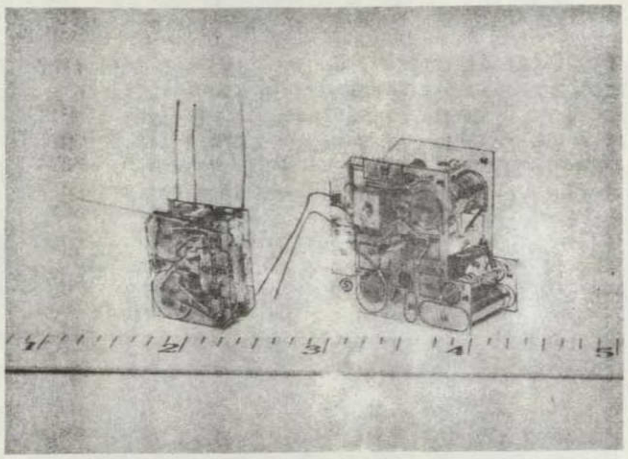
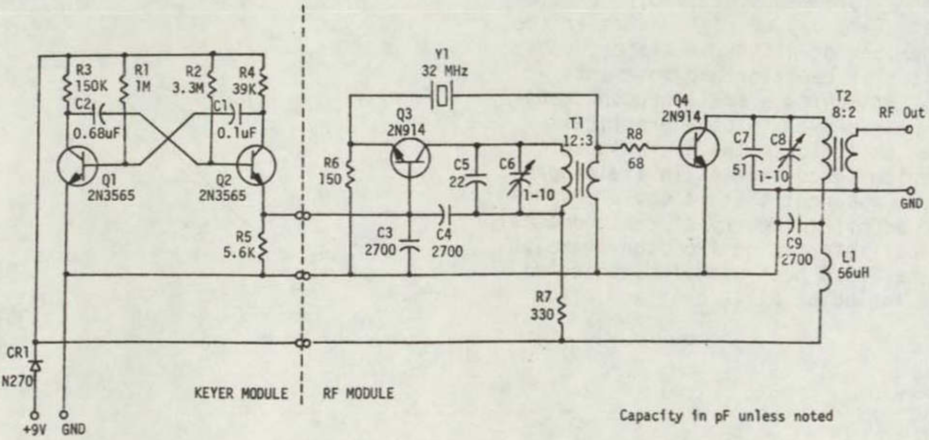


Figure 3: Transmitter construction



Capacity in pF unless noted

Figure 2: Transmitter circuit

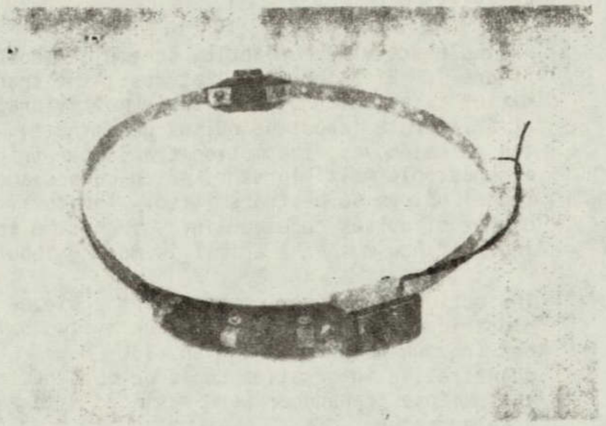


Figure 4: Transmitter collar assembly

The loop antenna was chosen because it is much less dependent on ground proximity and conductivity than a whip type and more efficient than various small ferrite-loaded loops tested. Some efficiency is lost when it is on an animal because of induced eddy currents in the neck. However, the deep nulls characteristic of small loops are no longer present when the collar is in place. It is also mechanically superior to a whip and not subject to snagging or breaking.

A waterproofed battery pack is attached to the collar adjacent to the transmitter case and the entire assembly is covered with a fiberglass-epoxy coat This makes the collar rigid and prevents flexing and bending which would cause eventual breakage or antenna detuning. Padding is placed on the inside of the collar for size adjustment for various animals, and wrapped with colored plastic tape for better visibility at a distance. A completed collar on a bear is shown in figure 5.

A summary of the transmitter characteristics is given in table 1.

Figure 5: Immobilized grizzly fitted with transmitter collar. A field strength meter used to tune the antenna is next to the collar.

Table 1: Transmitter Characteristics

Frequency	32 MHz
Output power	100 mW pulse
Pulse width	50 ms
Pulse repetition rate	1 per second (nominal)
Antenna type	resonant loop 11 inch diameter
Antenna impedance	50 ohms
DC input power	280 mW peak 18 mW average
Battery type	mercury, low temperature 9.3 volts, 4.5 Ah
Weight	
electronics	0.1 lb
battery	0.9 lb
complete collar	2.0 lbs
Operating lifetime	3 months standard 9 months with additional timer

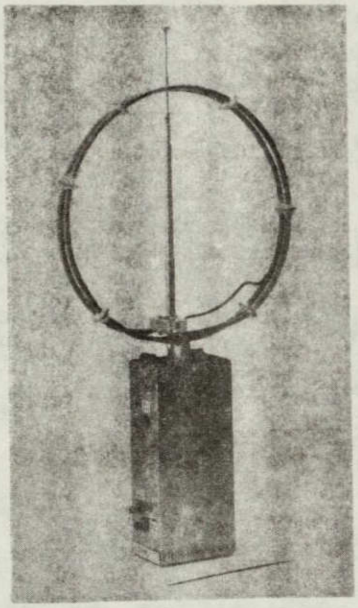


Figure 6: Portable receiver with loop antenna

Receivers and Receiving Antennas

The receivers used for location are conventional battery-operated AM dual-conversion superheterodyne types. A BFO was incorporated to permit reception of the unmodulated CW pulse from the transmitters. This approach gave maximum system range since it takes advantage of the ability of the human ear to detect the presence of received signals at signal-to-noise ratios considerably below unity.

The receivers were used with a variety of antenna types, depending on the tracking range and degree of mobility desired. Figure 6 shows a receiver equipped with a loop antenna which was used for tracking on foot at distances up to 2 or 3 miles. A sense antenna suppressed one lobe of the loop pattern to allow the direction of arrival of the signal to be determined.

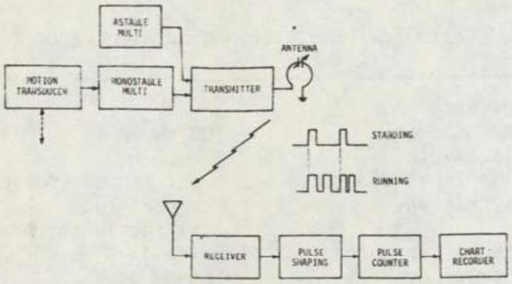


Figure 7: Activity telemetry system

If more range was desired when tracking on foot, the receiver was connected to a quad antenna (a two element array using one-wavelength wire loops rather than dipoles) which could be dismantled for backpacking. Ranges between 10 and 15 miles could be obtained with this antenna.

In many cases the instrumented animals could be located from roads by the use of 3-element yagi antennas mounted on vehicles, or from a base station at Canyon Village using a 5-element yagi on a 30 foot tower. Reasonably good bearings were obtained with these antennas in spite of their broad beamwidth by rotating the antenna and bisecting the angle between loss of signal points. Maximum ranges were between 10 and 15 miles.

Animals could be located from the air when they were in inaccessible country or had moved a considerable distance from their last known location. An 11 inch diameter loop antenna like the one shown in figure 6 attached to a strut on a fixed-wing aircraft gave ranges up to 20 miles. Greater range would be obtained with a more efficient antenna.

Experiments were also conducted with an unattended repeater station which could be set up in remote locations. The receiver portion of the repeater, connected to an omnidirectional antenna, was adjustable in sensitivity so that signals exceeding a predetermined level would trigger a transmitter on the same channel after a short time delay. The transmitter was connected to a directional antenna oriented toward the base station. Animals coming within the preset coverage radius of the station would trigger the repeater and cause the signal to be relayed to the base station.

TELEMETRY SYSTEMS

Slight modification of the location system described above made it possible to telemeter data about the animal's environment, condition, and behavior. Amplitude modulation was selected for compatibility with the receivers used for location. Pulse frequency or pulse duration modulation was used in most cases to minimize transmitter power requirements so that battery life would be as long as possible.

Activity

A simple activity monitoring scheme is shown in figure 7. With the animal at rest, the transmitter is keyed on by an astable multivibrator at a low rate (about 45 pulses per minute). When the animal moves, the motion transducer triggers a monostable multivibrator, which causes additional pulses to be transmitted. The total number of pulses received in a given time is an index of how much the animal is moving about.

The motion transducer consisted of a piezoelectric crystal which was struck by two ball bearings when moved or shaken (1). More quantitative information could be obtained if this simple transducer were replaced with an accelerometer.

In some cases sounds or calls made by animals or birds were of interest. A small AM transmitter was designed which broadcast sounds picked up by a built-in microphone. The power requirements were higher for the resulting continuous signal than for a pulsed signal, so a small solar panel was used to provide the power for the transmitter.

Heart Rate

A prototype system for monitoring the animal's heartbeat rate is shown in figure 8. The transmitter is keyed on by an astable multivibrator whose frequency is controlled by the amplified EKG voltage. The EKG waveform is sensed by two electrodes attached to the animal.

The astable multivibrator operates at 200 pulses per second so that frequency components up to at least 50 Hz in the EKG waveform will be transmitted with good fidelity.

The received PFM signal is demodulated by integrating the output of a monostable multivibrator triggered by the 200 pps subcarrier. The resulting EKG waveform is displayed on a portable oscilloscope or chart recorder.

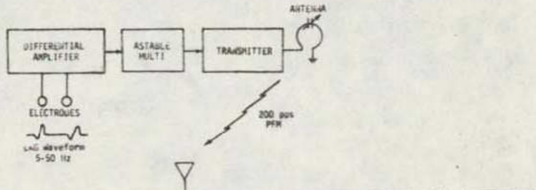


Figure 8: EKG telemetry system

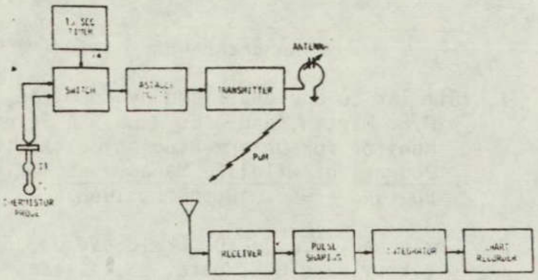


Figure 9: Two-channel body temperature telemetry system

Body Temperature

A body temperature measurement system is shown in figure 9. Temperature is sensed by a thermistor probe which is placed under the skin of the animal in the neck or shoulder region. As in the other systems, the transmitter is keyed on by an astable multivibrator. In this case, the pulse width is controlled by the resistance of the thermistor used as the temperature sensing element. A 15 second timing circuit alternately switches between each of two thermistors so that temperature at two different depths beneath the skin can be measured.

Figures 10, 11, and 12 show the system being tested on an elk in Yellowstone Park.

Another body temperature measurement system that has been used on a hibernating black bear is shown in figure 13. A small temperature-sensitive transmitter is surgically implanted or rectally inserted in the bear. The signal from the transmitter is picked up by a loop antenna placed on the floor of the den and recorded by equipment a short distance outside.

This approach eliminates troublesome wires and external attachments to the animal but is limited to very short ranges. Future experiments will use an implanted transmitter with an external repeater collar to obtain longer range.

Satellite Monitoring

In the future, satellites will probably play an important role in data collection for ecological and wildlife research programs. Two feasibility experiments recently carried out using the IRLS system were the first steps in this direction. The first, tracking of a migrating elk, is discussed in later papers in this session. In the second experiment, environmental data were telemetered from the den of a hibernating black bear (2).

Figure 10: Preparing to place temperature transmitter on an immobilized elk

Figure 11: Attaching temperature probe

Figure 12: Recording body temperature data

Figure 14 is a diagram of the den monitoring equipment. Temperature sensors were placed inside and outside the den to measure the influence of outside ambient temperature changes and of the bear's body heat on the temperature inside the den. Light sensors helped determine local weather conditions and whether the den entrance was covered with snow.

Collection of data by satellite is ideally suited for experiments conducted in inaccessible locations. In this case it considerably simplified our field problems in comparison with work in previous years at other dens with on-site monitoring and recording equipment. Further, when the bear left the den we were able to determine this from the data and visit the area within a day to make observations.

CONCLUSION

The tracking equipment described above has been used for several years in studies of both bear and elk. It has proved to be extremely useful to the field biologists, enabling them to make observations and gather data on animal movements and behavior that would be difficult or impossible to obtain using older methods. Other investigators are using systems of the same general type and complexity in studies of a wide variety of animals.

Many of the telemetry techniques that have been developed and are in use in aerospace and other fields have not yet been applied to wildlife research. For example, time-delay ranging using a transponder attached to the animal would have advantages over the triangulation methods generally used. There is room for much improvement and innovation in the antennas for animal-carried transmitters. Recently introduced low cost linear integrated circuits make narrow-band phase lock receivers for tracking appear much more practical than before. Large scale integration of semiconductor memories and logic is greatly reducing the cost and complexity of data sampling and storage devices that would be useful in many field projects. These and other new techniques and equipment could greatly expand the capabilities and applications of wildlife telemetry in the next decade.

ACKNOWLEDGEMENTS

This work was sponsored by the Environmental Research Institute and the Montana Cooperative Wildlife Research Unit, and partially supported by NSF grants 17502, GB-2672, and GB-6089, AEC contract AT(45-1)-1929, the National Geographic Society, and Philco-Ford Corporation.

REFERENCES

1. Similar to one described by Knowlton, F.F., P.E. Martin, and J.C. Haug, "A Telemetric Monitor for Determining Animal Activity", Journal of Wildlife Management, 32(4): pp. 943 - 948. October, 1968.

2. Craighead, J.J., F.C. Craighead Jr., J.R. Varney, and C.E. Cote, "Satellite Monitoring of Black Bear" (in preparation).

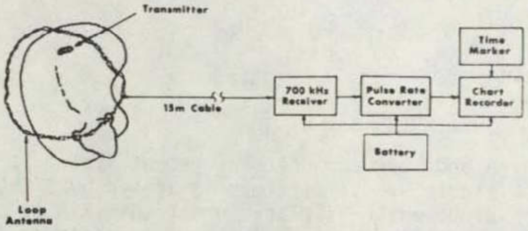


Figure 13: Temperature measurement system for a hibernating bear

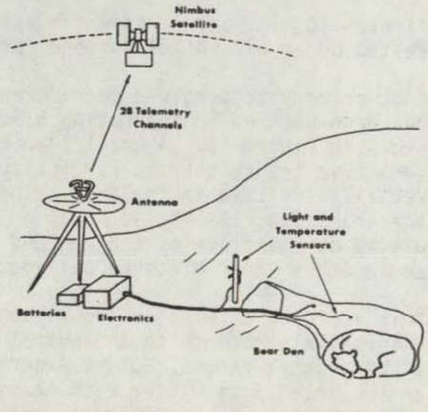


Figure 14: Monitoring a bear den with the IRLS system

Satellite Tracking of Elk

For the first time an animal has been tracked on the earth from a satellite

Frank C. Craighead, Jr., John J. Craighead,
Charles E. Cote, and Helmut K. Buechner

The authors are, in order: Adjunct Professor of Biology, Department of Biology, State University of New York at Albany, New York, and President, Environmental Research Institute, Moose, Wyoming; Leader, Montana Cooperative Wildlife Research Unit, U.S. Bureau of Sport Fisheries and Wildlife, University of Montana, Missoula, Montana; Space Technologist, Goddard Space Flight Center, Greenbelt, Maryland; and Senior Ecologist, Ecology Program, Office of Environmental Sciences, Smithsonian Institution, Washington, D.C.

12 March 1971

In a feasibility study to test the practicability of using the Interrogation Recording Location System (IRLS) (Cressey and Hogan, 1965; Cote, 1969, 1970) for tracking free-roaming animals, a female elk was fitted with a collar containing both an IRLS transponder and a Craighead-Varney ground-tracking transmitter (Craighead and Craighead, 1963, 1965a). The elk was tracked by the satellite and data were received during the entire month of April 1970. This was the first time an animal on the surface of the earth had been tracked by satellite. The feasibility of modifying IRLS equipment for this purpose was demonstrated. It is concluded that satellite data collection systems can have important applications for tracking animals in remote areas.

IRLS System

IRLS is an experimental system aboard the Nimbus 3 and 4 meteorological satellites to test the feasibility of locating and collecting data from remote instrumented platforms deployed on the surface of the earth. The IRLS system consists of the satellite, instrument platforms, and a central ground acquisition and command station (located in Fairbanks, Alaska). Each platform is equipped with a transmitter, receiver, and data encoder which are activated upon receiving a discrete 16-bit address code from the satellite. In operation the addresses of electronic platforms and anticipated times of platform overpass are programmed into the satellite on an orbit-by-orbit basis from the command station. As time elapses into the orbit, interrogations of platforms are executed at the preprogrammed times. During each interrogation the short-range distance from the satellite to the platform is measured by the satellite;

simultaneously, the platform transmits encoded sensor data to the satellite. The range information, time of ranging, and sensor data are stored in the satellite for readout at the end of the orbit (107 minutes later). A minimum of two interrogations is required per platform to determine its position. Through computer modeling, the locus of each range measurement forms a circular sphere in space with the satellite situated at its center. Each ranging sphere in turn intersects the surface of the earth (a third sphere) to project intersecting circles (Fig. 1). The platform must necessarily be located at one of the two intersections; the ambiguity is resolved through prior knowledge of the platform's position. The accuracy of locations increases with increasing distance between the satellite's orbital plane (ground track) and the platform. Data from passes nearly overhead translated into large errors in location in the geometrical calculations for position. The Nimbus III satellite was launched into a polar sun-synchronous orbit with equator crossings at local high noon and midnight, around the globe.

Instrument Collar

In cross-sectional view (Fig. 2) the IRLS collar is triangular in shape for conformance to the animal's neck. The interior sides were lined with foam rubber for protection against abrasions.

The prime power source for the instrument was provided by nickel-cadmium batteries contained in the left compartment of the collar. To insure a minimum lifetime of 6 months operation, an electromechanical timer was utilized to eliminate battery standby power during the 12-hour intervals between orbital overpasses. Solar cells were mounted to the sides of the collar to provide continuous charging during daylight hours. The IRLS electronic equipment utilized for this application was initially designed for operation on high altitude balloons; and only through the coordinated efforts of engineers and biologists in government, private institutions, and industry was the successful completion of the design possible. The detailed performance and physical specifications of the collar are listed in Table 1.

The Craighead-Varney ground-tracking transmitter (32 MHz) was installed in the lower compartment of the collar. A separate set of batteries and the antenna for this system were located at the top of the collar. Installation of the collar on the elk was accomplished by separating the instrument into two parts. It took 10 minutes to make the electronic connections and fasten the two parts of the collar on the animal.

Sensors

The design specifications of the IRLS system permit multiple sensory functions to be monitored by the platform (collar) for transmission and storage aboard the satellite In normal operation, data are available to experimenters or users within 1 to 2 hours of the overpass. Data formats of various lengths are available to meet specific requirements. The standard format consists of 22 data words encoded to ±1% accuracy (7 bits). Up to 30 such frames may be collected with each interrogation. The elk experiment required 10 channels to provide internal telemetry for the instrument and monitoring of external sensors. The data format selected for the experiment is shown in Figure 4. One such frame of data was collected during each interrogation of the instrument collar. Interrogations were programmed on each overpass for up to five samples for each sensor at intervals of 1.5 minutes. Temperature readings were obtained through thermistors mounted in the appropriate locations. The light-intensity sensor consisted of a standard photodiode mounted at the base of the antenna. A pressure transducer consisting of a bellows, acting on a potentiometer, and a vacuum reference was installed to measure altitude. The transducer bellows mechanism failed, and was inoperative throughout the experiment. Readings of external skin temperature were obtained by a thermistor mounted on a tension arm attached on the inside surface of the collar. The tension was calibrated to enable skin contact under normal activity conditions. Battery voltages were monitored directly, and the received signal strength was obtained at the output of the first intermediate-frequency stage. The electromechanical timer settings were translated into a linear voltage scale to enable orbit-by-orbit monitoring of the instrument's "on" window. Overlapping scales on two thermistors (-40 to $+10^{\circ}$C, 0 to $+50^{\circ}$C), located at the bottom of the collar to prevent solar hearing and to preclude thermal conductance from the battery power source, provided a range in ambient temperature from -45 to $+50^{\circ}$C.

Timer Control

A unique feature of the elk collar which provided a 6-month battery lifetime, despite the high power requirement of the IRLS equipment (150 milliwatts continuous standby), was the low-power electromechanical timer-control unit. The timer served to eliminate standby power by completely unloading the battery during the 12-hour intervals between orbital overpasses. During each overpass a 10-minute "power-on" period was initiated precisely as the satellite came into radio view. Orbital overpasses vary in absolute time from day to day, and the timer provided perfect synchronization with each orbit. Conceptually, the timer represented an electromechanical model of the physical conditions of the Nimbus orbit. In operation, two separate timers were used: a 24-hour earth rotation clock and a 107.417-minute orbital period clock. Contact points on the respective timers were engaged at 12-hour intervals coincident with each satellite overpass. Since the best low-power timers available could not maintain needed accuracy for 6 months, a periodic adjustment was required to maintain synchronization. This was accomplished by using the interrogation link to transmit a special coded sequence of binary bits whenever adjustment was required. The timer setting was monitored at each interrogation.

Pretesting

A mockup fiberglass collar (11.3 kg) to accommodate the IRLS electronic equipment was developed during the summer and fall of 1969. The model was tested for 90 days on a semitame female elk in a large corral at the National Bison Range, Moiese, Montana. The elk experienced no apparent discomfort, nor did the collar interfere with her daily activities. When lowering and raising the head during feeding the collar slid slowly back and forth on the elk's neck. No skin abrasions or excessive removal of hair resulted from the rubbing.

Meanwhile, the IRLS transponder and Craighead-Varney transmitter were packaged into a metal collar (11.3 kg) of the same configuration. Following the favorable results with the mockup collar, the IRLS instrument collar was placed on the same elk on 20 January 1970. Ten minutes after the elk recovered from the immobilizing drug (M99 -- etorphine) the instrument package was successfully interrogated by the Nimbus III satellite. Over the next 12 days interrogations were obtained on 16 orbits.

Having tested the system on an elk under controlled conditions, preparations were made for testing it on a free-roaming elk at the National Elk Refuge, Jackson, Wyoming. On 5 February two wild female elk were immobilized and fitted with mockup collars to condition them to accept the electronic collar. They were members of a herd of about 10,000 elk that are fed on the Refuge during the winter.

Experiment I

An elk wearing a mockup collar was to be captured and the electronic collar substituted for the dummy collar. Prior to the attempt on 19 February, personnel of the Refuge made a routine census. This disturbed the elk, and close approach to the selected animals was not feasible. A distant shot with a projectile syringe missed the collared elk and struck another animal, which became immobilized within 5 minutes with a dosage of 7 mg of etorphine. The instrument collar was fitted to this elk, which appeared to be in good condition. She was immobile for 30 minutes, recovering within 3 minutes after an injection of 14 mg of M-285 (diprenorphine), an etorphine antagonist. She rose without difficulty, and ran to rejoin the herd.

At noon on 20 February Nimbus III should have yielded data from interrogation, but failed to do so. Subsequent passes were likewise unsuccessful. It was later determined that installation of the instrument package had occurred during the hourly 6-minute speed-up cycle, disrupting the orbital period setting of the timer. Special commands from the satellite detected a 4 to 5 minute delay in the timer setting, which was then corrected by commands from the satellite. At noon on 22 February data were received from the animal. Simultaneously, field observations indicated that the animal's behavior was abnormal. An attempt to immobilze her and remove the collar failed. The elk died on the morning of 23 February, and an autopsy indicated a type of pneumonia not uncommon in the herd. This animal probably had an incipient stage of pneumonia, and the stress of being captured could have aggravated the infection.

Experiment II

On the morning of 1 April 1970 one of the two females wearing mockup collars was instrumented with the IRLS collar (Fig. 3). A veterinarian was on hand to ascertain the health of this elk. Her body temperature was normal (38.5°C), and she appeared to be in good condition. The drug was again administered by a projectile syringe fired from a gun. During the 27 minutes the elk remained immobile, engineers connected the electronic components of the two-piece collar. Immediately thereafter the elk received 12 mg of the antagonist. Within 3 minutes she arose, looked around briefly at the observers, and then lowered her head to nibble hay, after which she slowly ran off to join the herd about 200 m away. She immediately encountered another female. Both stood on their hind legs and struck with their forelegs, a behavior pattern which seems to establish dominance-subdominance relationships between individuals within the herd. The animal's behavior indicated a return to normal almost immediately after recovering from the drug.

On 8 April Nimbus IV was launched in an orbit slightly lower than Nimbus III and for 5 days the two satellites were orbiting together, one below the other. Under these conditions the window of the IRLS collar on the elk opened when Nimbus IV was overhead, and this instrument was the first to be interrogated by the new satellite. Good interrogations were obtained on three orbits prior to returning to Nimbus III for further monitoring of the instrumented elk.

Accuracy of Locations

During the period of operation 20 locations were obtained by satellite. On 5 orbits only one frame of data was received, precluding a location computation.

Ground sightings of the elk and radio fixes by field observers within the Refuge were used to determine the accuracy of the satellite locations. Since observations were made during daytime only, the resolution of nighttime interrogations could not be ascertained. Also, daytime observations could not coincide exactly in time with satellite overpasses, which imparts some degree of uncertainty to the references. Through interpolation of observed positions and radio fixes a set of reference points was derived.

The distance and direction of the satellite position with respect to the corresponding reference position (shown as origin) are plotted in Figure 5. The points on the plot indicated by x's denote locations obtained on near overhead passes where large errors were expected; three additional points obtained under these conditions yielded errors beyond the scale of the plot. Excluding the latter three points, the mean errors were: latitude 4.8 km; longitude 6.2 km. The location distributions shown in the figure fall into the following categories: <5 km, 5 points; 5 to 9 km, 7 points; >9 km, 5 points; and 3 points off scale.

The accuracy of locations can be improved by using low profile, omnidirectional, circularly polarized antennas. The particular antenna utilized for the elk experiment afforded coverage above 45° with respect to the horizontal. The most accurate locations are made when the satellite is between 10° and 50° above horizontal. This fact was evident in the large east-west errors (longitude), which are typically less than the north-south errors (latitude). The requirement for small-aperture antennas having moderate gain, circular polarization and light-weight characteristics present many problems to antenna designers. Progress is being made, and will continue as animal tracking grows in importance.

Analysis of Sensory Data

Five internal and five external sensory points were to be monitored with each interrogation, the format of each frame being organized as in Figure 4. From 1 to 29 April 86 measurements were obtained from each sensor, except the altimeter. The day and night distribution was 33 and 53, respectively. Clearly, the night passes yielded more data, which was attributed to improved antenna orientation and stability while the animal was at rest.

Trends observed in various sensors during April are plotted in Figures 6 and 7. The values plotted were selected from one representative data frame from each sequence of interrogations.

The steady increase in voltage levels during the first 3 days of the experiment showed that the solar panels functioned well in charging the batteries. Had charging not occurred, sufficient battery capacity existed to enable the instrument to operate for 6 months Charge levels remained well above nominal throughout the period, and showed no signs of degradation. Variations in day and night readings were caused by changes in battery leakage rates, which were a direct function of temperature. Trends in voltage and temperature were almost identical. The highest voltages were obtained on D_{15} and D_{20} where temperature readings were high (+11°C and +12°C, respectively). The battery temperature remained above ambient temperature during interrogations (as a result of heating effects of the battery under load and heat from the animal's body), but the trends between battery and ambient temperatures were identical (Figs. 6, 7). Previous studies in winter have shown considerable increase in battery temperature due to the warming effect of the animal's body (Craighead and Craighead, 1965b).

The accuracy of measuring skin temperature with a thermistor at the point of contact between the collar and the animal's skin requires further testing to determine the changes in insulating effect from sliding of the collar during feeding activity. Individual skin readings taken at 1.5-minute intervals during interrogation sequences suggest that the animal was at rest when the readings were constant and active when the readings were variable. 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 10 April could have resulted from continued pressure of the thermistor against the elk's neck as the animal lay with its neck resting on the collar. Similarly, 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 between the animal's body and the insulating material of its bed (Craighead and Craighead, 1966). An inverse relationship between skin and ambient temperatures, shown in about half the recordings (Fig. 7), could reflect alterations in insulation of the integument due to compaction of hair under the collar or thermoregulatory adjustments in the integument at ambient temperatures near 0°C. Although the data are inconclusive, they show the potentialities for studying thermoregulation by monitoring surface and subcutaneous skin temperature, as well as deep body temperature, using the IRLS system.

The light intensity readings showed perfect correlation with day and night conditions throughout the experiment. The nighttime readings remained identical in value, while the daytime readings fluctuated with light intensity. The values varied from bright sun to shaded sun, with the majority in the brighter area. No readings were obtained under forest canopy, but results indicate the feasibility of determining whether an animal is in open or timbered situations.

Movements of the Elk

Except for the longer movements, the locations obtained with the IRLS system were too inaccurate for determining the local minimum movements of the elk within the Refuge. For long-range migrations satellite locations of the elk's position could have yielded useful new information.

Contact between the elk and the satellite was lost on 1 May when the collar inverted. Communication was impossible with the antenna pointing groundward. Until 10 June 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 1,000 m, the strength of the signals improving with altitude. On 15 May when the elk had moved to the northern portion of the Refuge she was approached, using the directional receiver, and was observed to feed and run well with a band of 15 elk. The instrumented elk 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 on the Refuge. After remaining here and in the area of Uhl Hill and lower Spread Creek for 5 days the elk began moving up Spread Creek on 25 May, traveling southward into the Gros Ventre drainage to Slate Creek. There she joined a group of about 300 elk that annually calve in the area. When observed closely on 8 June she appeared to be in good physical condition. Most of the winter coat remained, and no abrasions or sores that might have been caused by the collar were observed. The elk was last located by ground-tracking radio on 10 June. The next contact was on 28 July in Cottonwood Creek about 20 km east of Slate Creek. On 14 November the instrumented elk was inadvertently shot 8 km from Cottonwood Creek by a hunter when the elk's head and shoulders were hidden in trees. This was immediately prior to her expected safe return to the National Elk Refuge. An autopsy of the animal showed that she was in good physical condition and pregnant; her kidney fat index was 175 (Riney 1955) and the femur marrow was white and did not compress (Greer 1968); the left ovary contained a corpus luteum 13 mm in diameter; the embryo was in the thread stage with membranes approximately 18 inches long.

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. These observations indicate that the detailed movements involved in an elk migration can be studied with a combination of ground and satellite tracking equipment. Such information is valuable in the management of elk populations.

Summary

Free-living animals can be tracked and monitored by satellite in natural environments, as indicated by the present feasibility study with the IRLS system. Satellite interrogations of an instrument collar on an elk at the National Elk Refuge were made over a period of 30 days, with a mean error of 4.8 km for latitude and 6.2 km for longitude. Improvement of the resolution of locations to within 1 km requires the development of low profile, omnidirectional, circularly polarized antennas.

Sensory data from the instrument showed the solar cells functioning so effectively that the number of batteries could have been reduced substantially to conserve weight. The data on skin temperature require verification by future experiments. They do, however, demonstrate the potential for monitoring physiological and environmental parameters with the 28 channels of the IRLS system.

The prototype instrument collar has weight limitations. Information derived from the experiment provided a basis for calculating a potential reduction in weight by at least 50%. A 5 kg instrument collar will make the IRLS system available for a wider variety of animals. Microminiaturization could reduce the weight of the IRLS package still further. However, IRLS is a highly regimented two-way system, and weight reduction has a limit. Weight limitations lie between 5 to 10% of the animal's body weight. There is, therefore, a need to develop satellite systems with instrument packages useful for birds and other small animals. The doppler-shift system has been proposed (Balmino, et al., 1968; Buechner and Maxwell, 1968) to bring the weight of the instrument on the animal to 50 g or less.

Satellite tracking and data-collection systems provide powerful new tools for studying biological phenomena, such as animal migration, and for obtaining information useful in the management of ecosystems and wildlife and fisheries resources. Additional cooperative research projects among biologists and engineers could advance this new technology to a widely applicable and economical system over the next decade.

Acknowledgements

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, in cooperation with the U.S. Bureau of Sports Fisheries and Wildlife. 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.

We thank biologists Harry V. Reynolds III and Vincent Yanonne, and graduate student Steven M. Gilbert of Montana State University, for assistance, especially in making field observations. The idea of tracking animals by satellite was proposed several years ago. It has been encouraged by Sidney R. Galler, Assistant Secretary (Science), Smithsonian Institution, and also by George J. Jacobs, Chief, Physical Biology, National Aeronautics and Space Administration, both of whom we acknowledge for their help and inspiration. Joel R. Varney, Research Associate, Montana Cooperative Wildlife Research Unit, University of Montana, played an important role in testing and applying the electronics systems throughout the study. James C. Maxwell, Staff Engineer, Ecology Program, Office of Environmental Sciences, Smithsonian Institution, also aided in the pretesting of the IRLS collar. Radiation, Inc., of Melbourne, Florida, conformed the IRLS instrument into the collar for the elk. Previous research under NSF (G-17502) and AEC AT(45-1)-1929 made possible the use of the ground radiotracking system. This study was supported by a grant (NASW-1983) to the Smithsonian Institution by the National Aeronautics and Space Administration.

References

Balmino, G., S. J. Criswell, D. L. Fernald, E. H. Jentsch, J. Latimer, and J. C. Maxwell. 1968. *Animal tracking from satellites.* Smithsonian Astrophysical Observatory Spec. Rep. No. 289, Cambridge, Mass. 40 p.

Buechner, H. K. and J. C. Maxwell. 1968. *Proposal for an experiment to track animals from artifical satellites.* Smithsonian Institution, Astrophysical Observatory, Cambridge, Mass. P 140-9-68.

Cote, C. E. 1969. *The interrogation, recording and location system experiment.* Goddard Space Flight Center Publ. No. X-733-69-336. 22 p.

______. 1970. *The interrogation, recording and location system experiment.* Geoscience Elec. Symp. Trans. IEEE, Spec. Issue. 5 p.

Craighead, F. C., Jr. and J. J. Craighead. 1963. *Progress in biotelemetry studies of grizzly bears.* Proc. 18th Ann. Instru. Soc. Amer. Conf. Biotelemetry Session, Chicago.

______ and ______. 1965a. *Tracking grizzly bears.* BioScience 15(2):88-92.

______ and ______. 1965b. *Yellowstone field research expedition V.* State Univ. of N. Y. at Albany Publ. No. 31, ASRC. 8 p.

______ and ______. 1966. *Radiotelemetry of large western mammals.* Prog. Rep. 1965-66. AEC Contract No. AT (45-1)-1929. 67 p.

Cressey, J. R., and G. D. Hogan. 1965. *The interrogation, recording and location system experiment.* Proc. Nat. Telemetering Conf. Sec. VI. 6 p.

Greer, K. R. 1968. *A compression method indicates fat content of elk (Wapiti) femur marrows.* J. Wildl. Mgmt. 32(4):747-751.

Riney, T. 1955. *Evaluating condition of free-ranging red deer* (*Cervus elaphus*), *with special references to New Zealand.* J. of Sci. and Tech., Sec. B. 36(4):429-464.

Table 1 Specifications of elk collar

Transmitter (FM)	
Power	15 watts
Frequency	466 0 MHz
Band Width	100 KHz
Receiver (FM)	
Sensitivity	-114 DBM
Frequency	401 5 MHz
Band Width	100 KHz
Antenna	Crossed Dipole, 2 DB gain, right circular
Sensors	10 (1% accuracy)
Batteries	Nickel Cadmium (20)
Solar Panels	Cadmium Sulfide (710 cm^2)
Weight (kg)	
Antenna	477
Antenna cover	350
Electronics	1 058
Electronics housing + solar cell cover	1 149
Batteries	2 097
Battery housing + solar cell cover	1 149
Transmitter/Receiver	1 149
RF housing	649
Collar materials	1 571
Ground tracking transmitter	717
Cable + connectors	908
Total	11 274

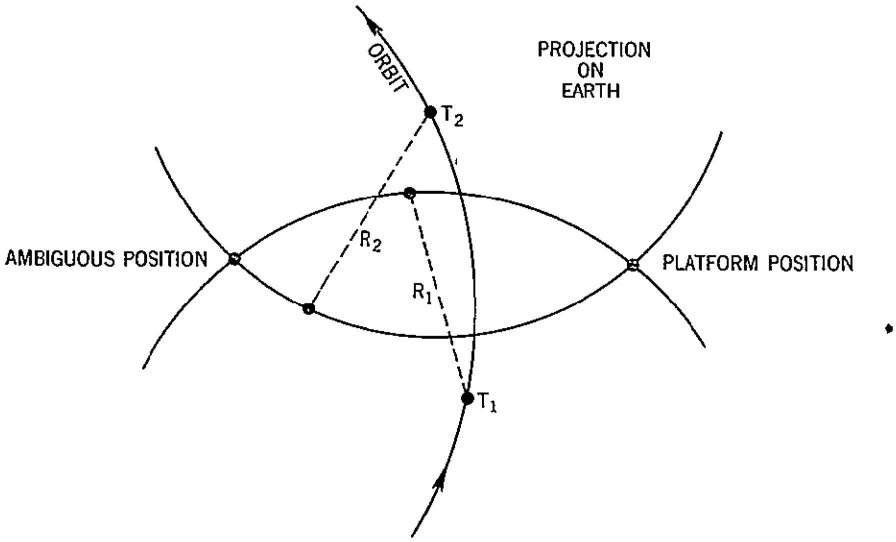


Figure 1: Short-range distances (R) from the satellite to the platform generate spheres in space with the satellite at the center. Where two such spheres intersect the earth, intersecting circles are formed on the earth's surface. The animal is located at one of the two points of intersection of the circles, the ambiguity being resolved by prior information of the animal's last position.

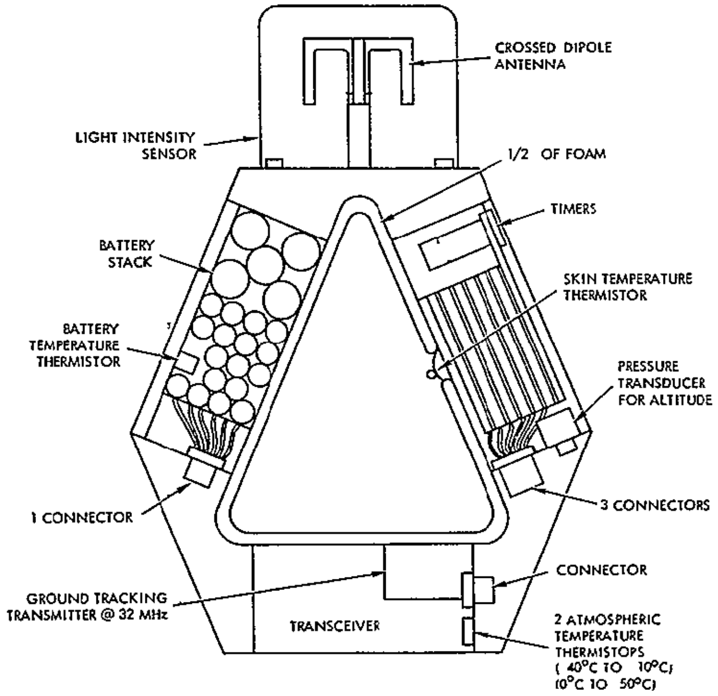
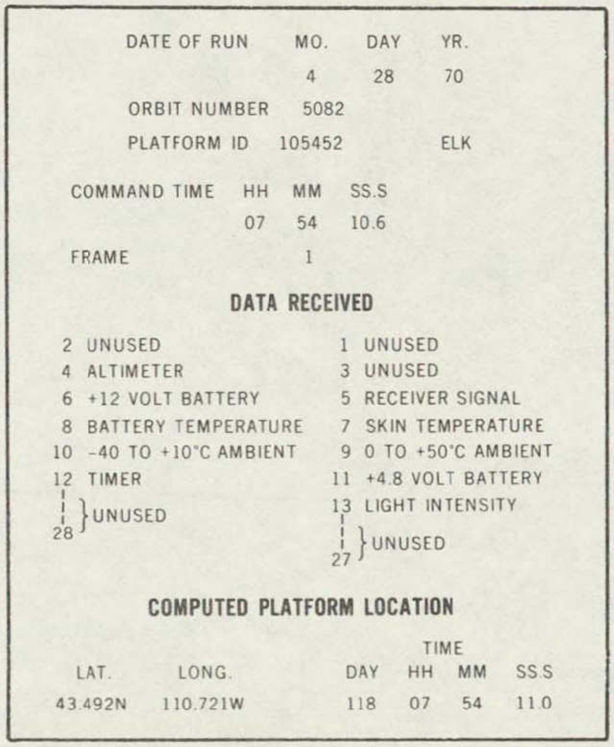


Figure 2: Cross-sectional view of IRLS collar

Figure 3: Elk with IRLS collar



```
          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
```

Figure 4: Format for computer printout of a frame of data

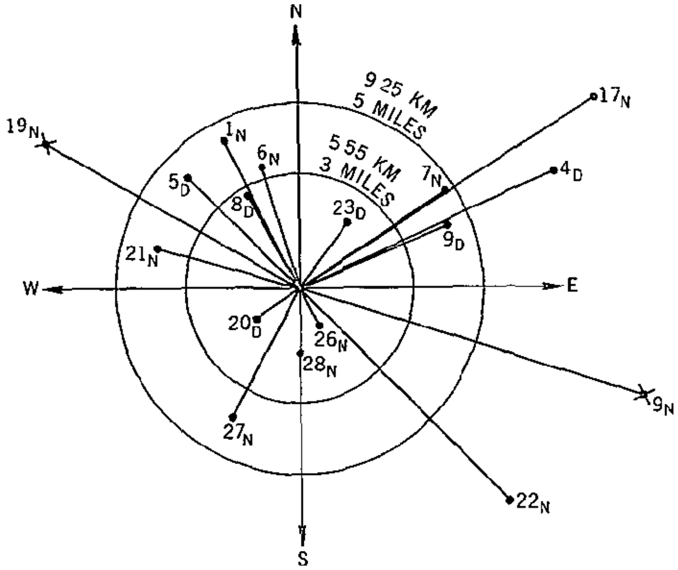


Figure 5: Resolution of positions determined by satellite. Numbers indicate day of month; subscripts indicate daytime (D) and nighttime (N). Origin represents zero error in distance; compass directions indicate direction of error from position observed on the ground.

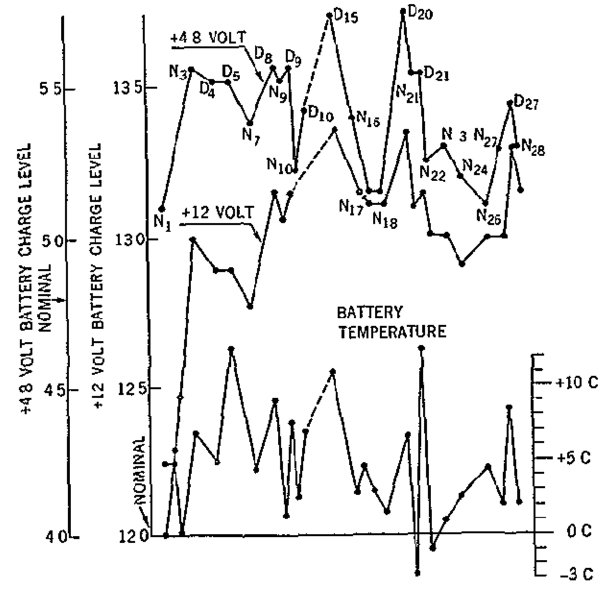


Figure 6 Battery voltages and temperature monitored by satellite. Letters indicate daytime (D) and nighttime (N); subscripts indicate day in April. Dotted line shows 5-day interruption at launching of Nimbus IV.

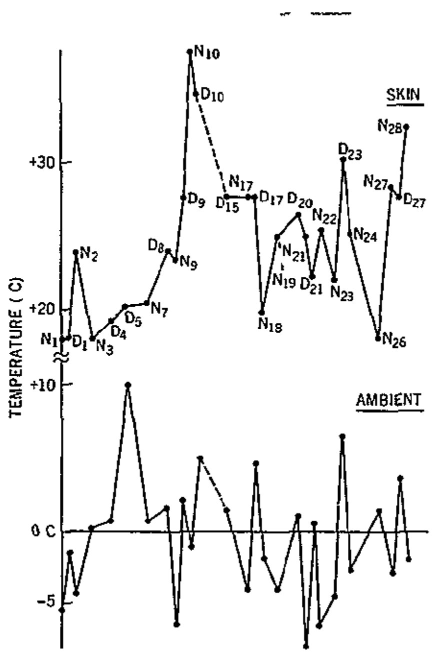


Figure 7: Ambient and skin temperatures monitored by satellite. Letters, subscripts, and dotted line same as figure 6.

Satellite Monitoring of Black Bear

Environmental data related to the winter activities of a black bear in "hibernation" were collected by satellite interrogations.

John J. Craighead, Frank C. Craighead, Jr.,
Joel R. Varney, and Charles E. Cote

The authors are, in order. Leader of the Montana Cooperative Wildlife Research Unit, Bureau of Sport Fisheries and Wildlife and Professor of Ecology, University of Montana, Missoula, Montana, Adjunct Professor of Biology, Department of Biology, State University of New York at Albany, New York and President, Environmental Research Institute, Moose, Wyoming, Research Associate, University of Montana, Space Technologist, Goddard Space Flight Center, Greenbelt, Maryland.

March 24, 1971

The application of modern electronics to wildlife research problems, using a variety of equipment and systems, has enabled researchers to obtain data on home ranges, movements, behavior, social interactions, and physiology of free-roaming animals; this information would be difficult or impossible to obtain using older methods.

Now the use of earth-orbiting satellites provides a new technique to locate and collect data from instrumented animals. It has unique advantages, including coverage of remote locations, such as the oceans and the polar regions, or surveying extremely large areas in a short period of time. An experiment, recently completed, used the Interrogation, Recording and Location System (IRLS) on the Nimbus 3 satellite to track and telemeter data from a migrating elk, Cervus canadensis (Craighead, et al. in press).

A feasibility experiment was recently performed to test the use of the Nimbus 3 IRLS System (Anonymous, 1966, Cote, 1969, 1970; Cressy and Hogan, 1965) for telemetering environmental and physiological data from the winter den of a "hibernating" black bear, Ursus americanus. The experiment was conducted with an IRLS unmanned data station (platform) originally developed for periodic global monitoring of geophysical, oceanographic, and meteorological data. The data gathering system, consisting of the platform, satellite, and a ground acquisition and command station was made available by the National Aeronautics and Space Administration.

A wild free-roaming black bear was fitted with a Craighead-Varney ground-tracking transmitter (Craighead and Craighead, 1963, 1965) and tracked to its winter den. During February and March of 1970, IRLS sensory equipment was placed in the bear's den, and data were transmitted to and stored aboard the satellite. The instrumentation procedure and our evaluations of equipment performance and of the sensory data obtained are discussed in detail.

Instrumentation Procedure

On October 16, 1969, a black bear was instrumented with a ground-tracking transmitter collar and then tracked with a portable directional receiver for 27 days while he selected and prepared a den for winter sleep.

The bear was lethargic when the den was checked on January 18, 1970. He had removed the radio collar and this was retrieved without disturbing the animal.

On February 14 the IRLS equipment was backpacked and pulled on sleds 5 km to the den. A hypodermic syringe mounted on the end of a 1.5 m jab stick was used to inject the bear with an immobilizing drug, phencyclidine hydrochloride (Sernylan). Immediately following injection, the bear came out of the den and ran about 20 m down the hill before stopping, he was then overcome by the drug. The immobilized bear was wrapped in a tarp, roped back up the hill and placed in front of the den. The sensors for IRLS satellite monitoring equipment were positioned both inside and outside of the den. At the same time, a loop antenna was placed around the bear's bed so that body temperature could be monitored by on-site temperature recording equipment. Ryan temperature recorders (a small clockwork-driven chart recorder) were placed where they would record both den and ambient air temperatures and were used to obtain a continuous temperature record to check on the temperature sensor data transmitted to the satellite.

A body temperature transmitter (Mackay, 1970) was rectally inserted in the bear and insulated with a soft paper anal plug. The bear was then moved back into the den, and the entrance was covered with snow.

The body temperature recording equipment was placed in an insulated box 15 m from the den. The IRLS equipment, connected to the sensors by a 100 m cable, was located about 90 m uphill where the antenna had a relatively unobstructed coverage of the sky.

Data were received from the den by satellite for 17 days until the IRLS equipment batteries were nearly exhausted and communication with the satellite became intermittent. Body temperature was recorded on-site for 4 days following immobilization until the transmitter either failed or was expelled.

The den was visited on March 7 to recharge the batteries. Normally this is accomplished by solar panels on IRLS platforms, but they were not used because of possible difficulties with heavy snowfalls. The equipment was placed in operation again on March 8.

Another trip to the den was made on March 12 to replace the body temperature transmitter and to modify the instrumentation set-up to allow connection of the on-site body temperature recording system to the IRLS equipment.

The bear was again injected with an immobilizing drug, and as before, he left the den and moved a short distance through deep snow before the drug took effect. He was hauled back up the hill, and a new rectal temperature transmitter was inserted. The first transmitter was not found during a quick check of the den floor and litter. New charts were placed in the Ryan temperature recorders inside and outside the den. A radio collar for tracking and location from the ground was also placed around the bear's neck to follow his movements when he left the den in the spring. After the IRLS sensors were repositioned, the bear was returned to his den, and the entrance was resealed with snow. Equipment changes and connections were made to permit monitoring of the body temperature readings by satellite as well as the temperature and light readings already being telemetered.

On March 13 satellite telemetry data indicated the bear was in his den. On March 14, however, temperatures within the den dropped to near ambient levels, and the light sensor inside the den indicated that the entrance was open. A trip to the den on the evening of March 14 showed that the bear had left. Signals from the radio collar on the animal showed that he had moved about 2 km to the north.

Data from the sensors continued to be collected by the IRLS equipment until the batteries were exhausted on March 23. The equipment was removed from the den on April 4. Bearings taken from the radio collar on the bear at that time showed that he had remained in the new location. The bear was captured and the radio collar was removed in May of 1970.

IRLS System

A sketch of the basic components of the IRLS monitoring system is shown in figure 1. Light and temperature sensors were placed at various points of interest. The satellite communications equipment was connected to a 1.2 m diameter antenna mounted on a tripod. Power for the equipment was provided by two lead-acid automobile batteries enclosed in a styrofoam box and buried in the snow to help prevent freezing.

A simplified block diagram of the den monitoring equipment is shown in figure 2. It consists of the sensors, excitation and control circuitry for the sensors, and the IRLS equipment.

The light and temperature parameters are measured by variable resistance transducers and converted to DC voltages by the sensor excitation and control circuitry. The output of each sensor channel is a precision voltage that is proportional to the parameter being measured and of the proper magnitude and polarity for input to the IRLS system. To reduce the battery drain of the system the sensor control circuits apply excitation voltages to the sensors only during the time that satellite interrogation is in progress.

The output voltages of the sensor channels are sampled by the IRLS electronics and are converted to digital form suitable for transmission to the satellite.

The satellite interrogation sequence consists of several steps. Before the orbit on which the interrogation is to occur, a ground station (Fairbanks, Alaska) transmits a series of commands to the Nimbus 3 satellite that determine which platforms, located world-wide, are to be interrogated and the times at which the interrogations should be made. At the programmed time, the satellite comes within radio view of the IRLS platform to be interrogated and begins to transmit a coded address signal. When the IRLS equipment on the ground receives the address signal, it replies to the satellite by transmitting a response signal. The response signal prepares the satellite to store data, and the satellite then transmits an interrogation signal to the IRLS platform. The platform samples each of the sensor channels, encodes the data, and transmits it to the satellite where it is stored for later readout. The entire sequence takes only a few seconds.

During the interrogation sequence, the satellite also determines the distance to the platform by measuring the time between the sending of the interrogation signal and the response from the platform. This distance information is stored with the rest of the data and allows the location of the platform to be calculated. Since the exact location of the satellite at any time is known from its orbit parameters, each range measurement allows an imaginary circle to be drawn on the earth's surface; the platform must be located on this circle. A second interrogation sequence provides data from which another circle can be drawn which intersects the first at two points, on one of which the platform is located. The two points are sufficiently distant from one another to allow the station to be located without ambiguity by using previously known locations and deduction.

As the satellite continues on its orbit, it interrogates other IRLS stations and stores data. When it completes the orbit and passes over the

Fairbanks tracking station again, all data are transmitted from the satellite to the ground station and a new set of commands is loaded into the satellite for the coming orbit.

The Nimbus 3 satellite is in a polar sun-synchronous circular orbit, with a period of 107 minutes and an altitude of 1100 km. It passes within communications range of the same point on the earth's surface about every 7 orbits, or every 12 hours. Data can thus be obtained from an IRLS platform at a fixed location at 12 hour intervals. Interrogations for the bear den occurred near noon and midnight each day.

After the platform data has been collected from the satellite by the Fairbanks tracking station, it is sent by telephone line and microwave link to the Nimbus data processing center at NASA's Goddard Space Flight Center near Washington, D. C. After processing, the data is printed out by computer and mailed to the experimenter.

For a more detailed discussion of the IRLS system see Anonymous, 1966; Cote, 1969, 1970, Cressy and Hogan, 1965.

Sensor Placement

The light and temperature sensors were placed in the den as shown in figure 3. One temperature sensor (T2) was located directly under the bed material and the others (T1, T3, T4, T6) were arranged to measure temperatures at various spots in the rear and near the entrance to the den. A light sensor (L1) inside the den was pointed at the entrance to monitor the amount of light entering and to record if the snow seal was broken, an indication that the bear might have moved out of the den. A Ryan temperature recorder was placed near T3 to provide a continuous record of the den temperatures. A 7 cm spike attached to each sensor secured them to the den floor or wall.

Temperature sensors T5, T7, and T8 were secured to a pole outside the den entrance at different heights above the ground. Sensor T8 was buried beneath the snow, T7 was 0.6 m above the surface, and T5 1.2 m. Additional snowfall later buried T7.

Light sensors L2 and L3 were also placed on the pole outside the den. L2 was pointed at open sky and L3 at the snow surface below the den entrance.

Evidently temperature sensor T4 was dislodged from its original location during the second instrumenting on March 12. Because the identify of the sensor was uncertain at the time, it was replaced in the center of the bed with T2 (see figure 3). Later checking of field notes permitted the identification of the sensor.

Body Temperature Recording System

A block diagram of the body temperature recording system is shown in figure 4. The system consists of a temperature-sensitive transmitter implanted or inserted in the bear, a wire loop antenna located near the animal, and receiving equipment consisting of a broadcast band receiver, pulse rate converter, and chart recorder.

The body temperature of the bear is sensed by the transmitter and causes changes in the rate of a series of short pulses broadcast by the unit. These signals are picked up by a loop antenna placed under the animal as shown in figure 4 and detected by a receiver set up outside the den. The demodulated pulses from the receiver are counted and converted to a DC voltage by the pulse rate converter for input to the chart recorder. A continuous record of body temperature results.

Data were initially recorded by an on-site chart recorder. Additional equipment changes and connections were made during the March 12 visit to permit monitoring of the bear's body temperature by satellite.

Analysis of Sensory Data

Ryan Temperature Recorder Data

Continuous den and outside ambient temperature records for the period of the experiment are shown in figure 5. The recorder inside the den was placed 60 cm off the floor and approximately 80 cm from the bear's bed as shown in figure 3. The outside recorder was suspended from a tree in a shaded location near the den entrance.

Den temperature remained fairly constant, with a maximum change of 4°C and little cyclic day-night variation, during the first 4 weeks (Feb. 14 - Mar. 12) while the bear was in the den. Outside temperatures during this period ranged from a low of -18°C to a high of 3°C, a variation of 21°. The den temperature was near freezing or slightly below. The average den and outside temperatures were -1.3°C and -5.3°C, respectively, a difference of 4.0°. Cyclic day-night outside temperature variations are apparent for most days.

The small variations in den temperatures tend to follow the long-term trend of the outside air temperature. The minimum den temperature of -4°C on February 19 coincides with a low of -15°C outside, and the gradual increase in the den temperature from -4°C on February 19 to -1°C on March 2 follows a warming trend outside. A slight dip in den temperature on March 6 follows two low outside readings. However, two days of -18°C lows outside on March 10 and 11 had no effect on den temperature. The probable explanation for this is the insulating effect from a snowfall prior to March 10 which covered the den entrance more deeply than before.

The second recording period began on March 12. The den temperature remained near -1°C for the first few days. The bear probably left the den before noon on March 14. With the bear no longer present the den temperature declined gradually, following declining outside temperatures, and reached -6°C on March 19, which coincides with an outside low of -15°C. Until the sensors were removed on April 4 the den temperature continued to follow the outside temperature to a greater extent than when the bear was present, the maximum variation of den temperature was 6°, while the outside temperature showed a maximum fluctuation of 18°. The average temperature inside the den was -3.6°C and -5.4°C outside, a difference of 1.8°. Cyclic day-night variations in den temperatures are noticeable, especially between March 28 and April 3, these variations did not appear when the bear was in the den.

IRLS Temperature Data

Temperature readings obtained from the den sensors by the IRLS system have been converted from telemetry voltages to degrees Centigrade and are shown in figures 6 through 9. Data were not received on some days because the satellite did not pass within communication range of the station, and the equipment was not operating between March 3 and March 9 because of low batteries.

Sensors T1, T3, and T6 measured air temperature in the den at different distances from the entrance, with T1 in the extreme rear, T3 midway to the entrance, and T6 near the entrance (see figure 3). T1 remained at a nearly constant temperature of -2°C as long as the bear was in the den. The low outside temperatures on February 18-21 caused only a -0.5° depression at T1. Sensors T3 and T6 were influenced more by outside temperature and showed changes of 5° during the same period (Fig. 6).

The second immobilization of the bear on March 12 is marked by a vertical dotted line on the temperature curves. All three sensors showed small temperature rises on March 13 and 14 which were probably due to the bear's movements inside the den. When the bear left the den on March 14, temperatures dropped, they then began to follow the outside temperature changes to a greater extent than before. Also the differences between the three sensors were less when the bear was no longer in the den.

Data from sensors T2 under the bed and T4 on the floor of the den near the bed are plotted in figure 7. After initial placement, the temperature of T2 climbed from 0.5°C to a high of 29°C in a 10-day period because of the warming effect of the bear's body heat. Average temperatures were near 21°C for a large portion of the time from February 20 to March 3. The readings of T4, which measured the temperature of the den floor, remained low, they were near -1°C during the same period.

When the station batteries were recharged on March 9, the data showed that the bear had changed his position in the den. T2 temperature dropped to -1°C, while T4, now influenced by the animal's body heat, rose.

After the second immobilization, T4 was moved to a location in the bed near T2. On March 13, both T2 and T4 showed temperature rises from body heat. On March 14, however, their temperatures dropped and remained low thereafter, indicating that the bear was no longer in the den. From March 14 to 23, temperatures from T2 and T4 were similar to those of the other sensors in the den.

Data from sensors outside the den are plotted in figures 8 and 9.

Sensor T7 (figure 8) was initially above the surface of the snow and followed air temperature variations closely. From about March 2 on, however, it shows less change with air temperature and was probably covered by new snowfall at this time. Examination during the visit to the den on March 12 confirmed that the sensor was covered.

Sensor T8 (figure 8) was buried in the snow and remained at a relatively constant temperature, which only varied about 5° around an average temperature of -5°C.

Sensor T5 (figure 9) recorded air temperature for the entire time since it was initially placed 1.2 m above the snow surface and remained uncovered. Readings from this sensor correspond closely with the air temperatures measured by the Ryan recorder (figure 5).

Sensor T9 measured air temperature at the location of the sensor excitation and IRLS platform electronics, which were located on the hillside about 30 vertica m above the den entrance. The readings correspond with those of T5 and the Ryan recorder.

Data from sensors T1, T2, T3, T4, and T5 are plotted simultaneously in figure 10 for comparison. The temperature points for each sensor are connected by lines for easier visibility and do not represent temperatures between data points. The influence of outside temperature on T3 and its lack of effect on T1 are apparent. The moderating effect of body heat from the bear on den temperatures is also evident in the way that temperatures from all inside sensors followed outside temperatures after the bear left the den.

Average temperatures inside the den with the bear present ranged from 18.1°C in the bed to -3.0°C near the entrance, while outside air temperature was -6.7°C. After the bear left the den, inside temperature at the rear of the den dropped to about 2° above the average outside temperature (Table 1).

Light Sensor Data

Telemetry data from the three light sensors are tabulated in figure 11.

Table 1

Average Temperatures in Den

Sensor location	Average Temperature Bear in den (2-15 to 3-13)	 Bear absent (3-14 to 3-23)
Rear of den (T1)	-1.7°C	-3.0°C
Bed (T2, T4)	18.1	-2.9
Top front of den (T3)	-3.0	-4.3
Outside ambient (T5)	-6.7	-5.0

L2 was located outside the den and pointed at open sky at an angle of 45° from horizontal. The voltage readings from the sensor showed day-night variations very well; it showed zero readings at night and readings in the 5 volt region during the day. The variation between day readings, however, is not enough to determine details of weather conditions such as the amount of cloud cover. Further experimentation with sensor scale factors may provide better resolution for future experiments.

Light sensor L3 was also located outside and was pointed down at the snow. An unexplained 2.35 volt offset is evident in the readings between February 15 and March 12. After the equipment modifications for body temperature monitoring were made on March 12, however, the problem disappeared and normal readings were obtained.

Sensor L1 was inside the den pointing at the entrance. Zero readings between February 15 and March 13 show that the entrance was covered with snow and that the bear did not venture out. The day reading on March 14 showed that the den entrance was open for the first time. This together with low bed temperature readings led to the suspicion (later verified) that the bear had left the den. Readings on subsequent days showed that the entrance remained open.

Body Temperature Data

On February 14, temperature data from the rectal transmitter was not received for the first 6 hours after the bear was placed in the den to recover from the effects of the immobilizing drug. This was probably because the bear did not immediately move all the way back into the den and lie over the loop antenna encircling his bed.

The system began to record data around midnight and continued for the next 4-1/2 days until 1800 on February 19. Data taken from the recording at 1 hour intervals is plotted in Figure 12.

The body temperature of the bear reached an equilibrium value of approximately 35.3°C by the morning of February 15 and remained there for the next two days. This corresponds closely to a temperature of 35.6°C taken previously with a rectal thermometer from another black bear immediately following immobilization; it also corresponds closely to telemetered temperature readings obtained from a thermistor probe inserted 4 cm into the neck muscle of a black bear in his winter den (Craighead and Craighead, 1965). Figure 12 shows that the nighttime body temperature was slightly lower than the daytime temperature (about 0.5° variation); however, the amount of data is not sufficient to allow any conclusions to be drawn about nychthemeral body temperature fluctuations.

The telemetered temperature dropped to 33.8°C at 1500 on February 17, and remained in that vicinity through February 18. On February 19, it made several large excursions before data stopped at 1600 hours. The reason for the large apparent changes is not clear, and two causes are possible. The transmitter could have been expelled by the bear with consequent temperature changes during the process. The transmitter was not tested below 20°C, but it is probable that it would stop operating at freezing temperatures after being expelled. The other possibility is that the waterproofing of the transmitter was not adequate and fluids in the colon caused it to fail; the apparent temperature changes could have been caused by erratic operation.

After a new transmitter was inserted in the bear on March 12, data were received for two short periods. The data are shown in figure 12. The indicated temperature during the first of these periods varied between 35.6 and 36.7°C. Temperature during the second period increased from 34.8 to 35.5°C. The gaps in the data are due to the bear moving around in the den and out of range of the loop antenna. Disturbing the bear a second time probably reduced his lethargy, which might account for the higher body temperature readings. He left the den on the morning of March 14, and no further data were obtained.

Neither of the body temperature transmitters were recovered for recalibration after the experiment, so the data should be accepted with reservations.

Satellite interrogations did not occur during the periods when body temperature data were being recorded (see figure 12), so no body temperature data were telemetered by the IRLS system. This can be accomplished in future experiments. Itmmay also be possible in future experiments to implant the transmitter in the bear's abdominal cavity; this will result in greater accuracy if the problems attendent with surgery under rigorous field conditions and the additional stress on the bear can be overcome.

Location Data

The den locations computed from satellite data are shown in figure 13. A location was obtained on each orbit in which two or more frames of data were received by the satellite. A total of 29 locations, approximately one per day during the time that the equipment was operating, were computed during the experiment.

Three location points were obviously erroneous (more than 15 km from the known location), and are not shown in the figure. For the remaining 26 points, the average location error was 3.77 km and the root-mean-square error was 4.31 km. All location points lie within a circle of 7.25 km radius.

Since the den location was known in this experiment, the location capability of the IRLS system was not required. The data are of interest, however, since they give an indication of the accuracy that could be obtained with the equipment under different circumstances where location is desired but is unknown.

Discussion and Summary

Physiological data from free-living animals and environmental data related to their activities and behavior can be collected by satellite interrogations. The IRLS system provides 28 channels of information at 12 hour intervals and has the capability for rapidly collecting and processing a wide range of ecological data from remote unattended locations.

Sensory data collected in this feasibility experiment with a hibernating black bear showed that the temperature in most locations in the den remained near freezing. Average temperature recorded in the bear's bed was 24.8°C above outside ambient. Other points in the den were 3° to 5°C above outside temperatures. After the bear left, average den temperature was 2°C above the average outside ambient temperature. The body temperature of the bear reached an equilibrium value of approximately 35.3°C with about a 0.6° day-night variation.

Bears lose relatively little body weight during the period when they are in the winter dens; the majority of weight loss occurs between the time they emerge from the den in the spring and the time when natural food becomes plentiful in late June. This fact, together with the relatively high body temperature of the bear during the winter, indicates that the amount of body heat lost within the den is very low.

The den air temperatures measured during this experiment are lower than might be expected and show that little heat is radiated from the bear's body. Loss of body heat by air circulation is low in the still air of a den sealed by snow, and heat loss by conduction is reduced by the insulating bed material which envelops most of the bear as it is curled in sleep. Thus the bear is surrounded by a microclimate. This microclimate is relatively confined, as indicated by high temperature readings in the bed and much lower readings from sensors located only a short distance away.

Further experiments with more temperature sensors would allow better definition of the extent of this microclimate and of temperature gradients near the animal. Thermal flux and radiation sensors could be placed in the bed and in the air strata above the animal to measure net heat loss. These measurements would lead to a better understanding of the energy balance and heat conservation mechanisms of hibernating bears.

The results also demonstrate the way in which temperature and light sensors could be used in future experiments to gather additional information on whether and how often a bear leaves the den in the winter and early springs, movements within the den, and other behavioral data. With transmitter implants, information on body temperature and heart rate can also be obtained by satellite utilizing IRLS equipment. With appropriate sensors, other physiological parameters can be measured and studied.

These techniques would be of special value in studies of polar bear. For example, environmental parameters from a number of polar bear dens scattered throughout the Arctic could be simultaneously monitored. Information about the location, heart rate, and body temperature of instrumented polar bears obtained with improved equipment and techniques would aid in understanding the thermoregulatory processes (Øritsland, 1970) and biological rhythms in these large carnivores, as well as their patterns of movement (Flyger and Townsend, 1968).

The IRLS system's flexibility and usefulness could be increased by data sampling at closer than 12 hour intervals. This could be accomplished by auxiliary equipment which stores data for later readout. Use of a timer is desirable to turn the system off between interrogations to extend battery life.

On-site electronic systems, such as the body temperature system used in this experiment, can be connected to the IRLS system for interrogation by satellite. However, where on-site recording systems can be tended without great logistic problems, they are less expensive than the satellite system and can provide equally accurate data from a wide range of sensors. The value of satellite monitoring increases directly with the remoteness of the area where data is to be collected and with the need for near simultaneous recording from a large number of stations.

A detailed cost comparison of satellite monitoring versus on-site recording is difficult to make for the den monitoring experiment described, since the satellite system was designed and funded for meteorological purposes and we merely tapped some of its unused potential. Both current and planned satellites (Nimbus, ERTS, and others) have data collection systems with a capability which greatly exceeds the use that has or will be made of them.. They could easily accommodate many feasibility experiments like this one with little additional cost. In the future, as greater use is made of satellite data collection systems, the ability of a single satellite to service many hundreds or thousands of ground stations will make it the most cost-efficient method of gathering data in many situations.

Acknowledgements

This project was a joint endeavor between the National Aeronautics and Space Administration, the Montana Cooperative Wildlife Research Unit, the Environmental Research Institute and the National Geographic Society. The experiment was conducted in Yellowstone National Park in cooperation with the National Park Service and the Bureau of Sport Fisheries and Wildlife,

We thank Jay Sumner, Harry Reynolds III, Vincent Yanonne, and James Claar for assistance in the field, and Helmut K. Buechner and George J. Jacobs for helping to coordinate the project

References

Anonymous, 1966. *IRLS platform electronics and telemetry equipment instruction manual,* Radiation, Inc. (NASA-GSFC Contract NAS 5-9559, June 1966).

Cote, C. E. 1969. *The interrogation, recording and location system experiment.* Goddard Space Flight Center Publication No. X-733-69-336. 22 P.

_______. 1970. *The interrogation, recording and location system experiment.* Geoscience Electronics Symposium, Trans. IEEE, Special Issue. 5 P.

Craighead, F. C., Jr., and J. J. Craighead. 1963. *Proceedings 18th Annual Instr. Soc. Amer. Conf. Biotelemetry Session.*

_______ and _______. 1965. *BioScience* 15. (2):88-92.

_______ and _______, C. E. Cote, and H. K. Buechner. 1971. *Satellite Tracking of Elk.* In press.

raighead, J.J. and F.C. Craighead. 1965. *Report on Radiotracking and Telemetering Systems for Large Western Mammals.* 68 pp. Unpublished.

Cressey, J. R. and G. D. Hogan. 1965. *The Interrogation, Recording and Location System Experiment.* Proceedings of the 1965 National Telemetering Conference. Pp. 96-101.

Flyger, V. and M. R. Townsend. 1968. *The Migration of Polar Bears.* Scientific American, 218 (2):108-116

MacKay, R. S. 1970. *Biomedical Telemetry.* John Wiley & Sons, Inc., New York.

Øritsland, N. A. 1970. *Temperature Regulation of the Polar Bear* (*Thalarctos maritimus*). Comp. Biochem. Physiol. 37:225-233.

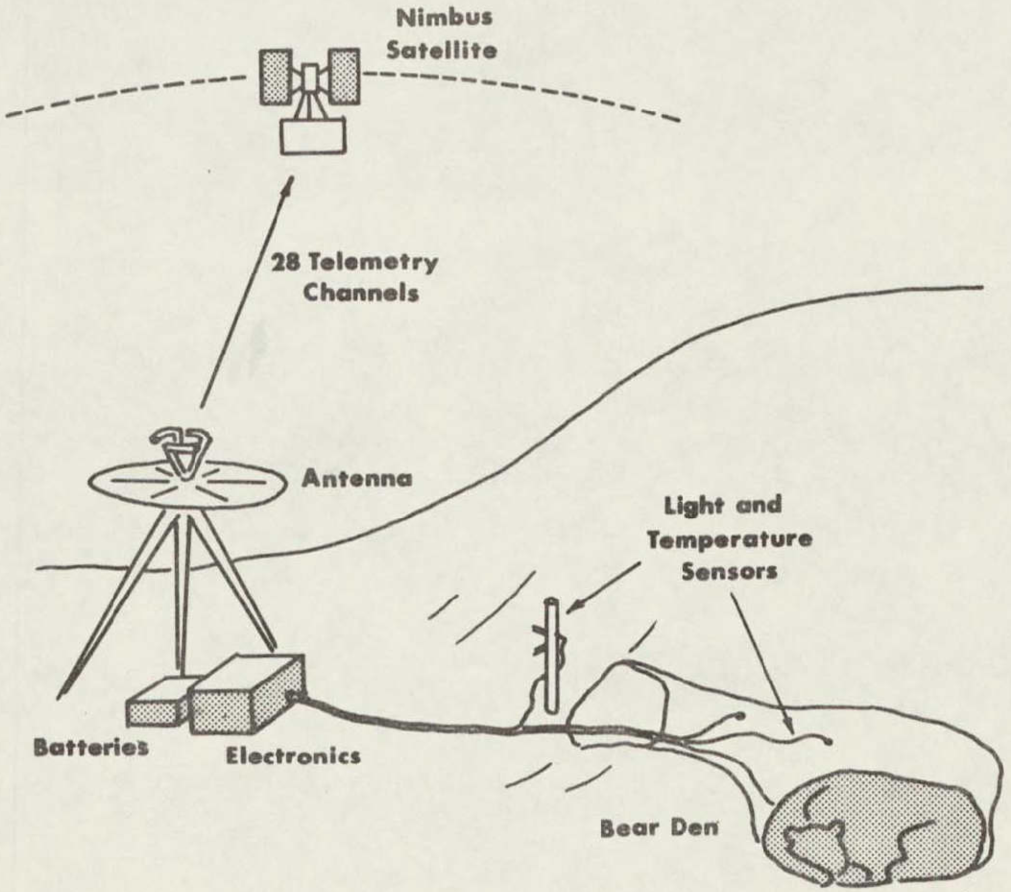


Figure 1: Bear den instrumentation with IRLS equipment. Temperature and light data from sensors placed in the den are encoded and relayed to the Nimbus 3 satellite.

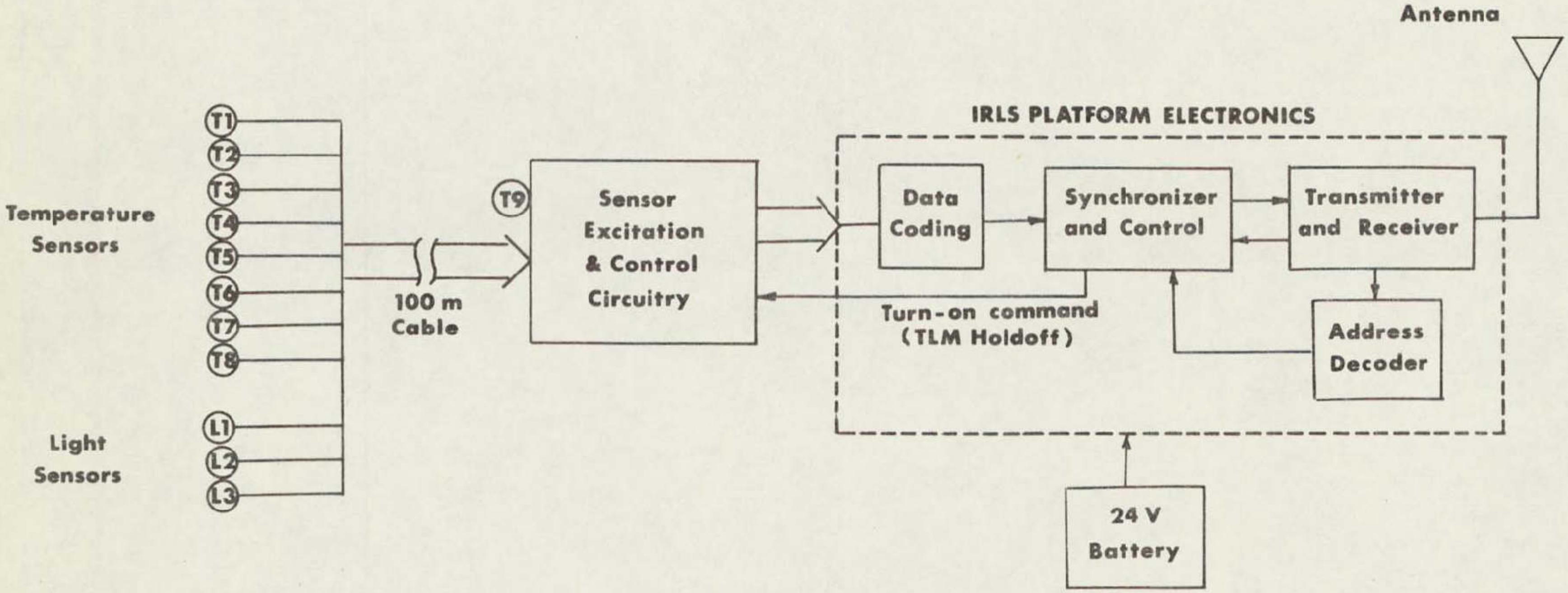


Figure 2: Block diagram of the IRLS portion of the den instrumentation equipment. The sensors are activated upon command by the satellite and the resulting output voltages are sampled and encoded for transmission to the satellite.

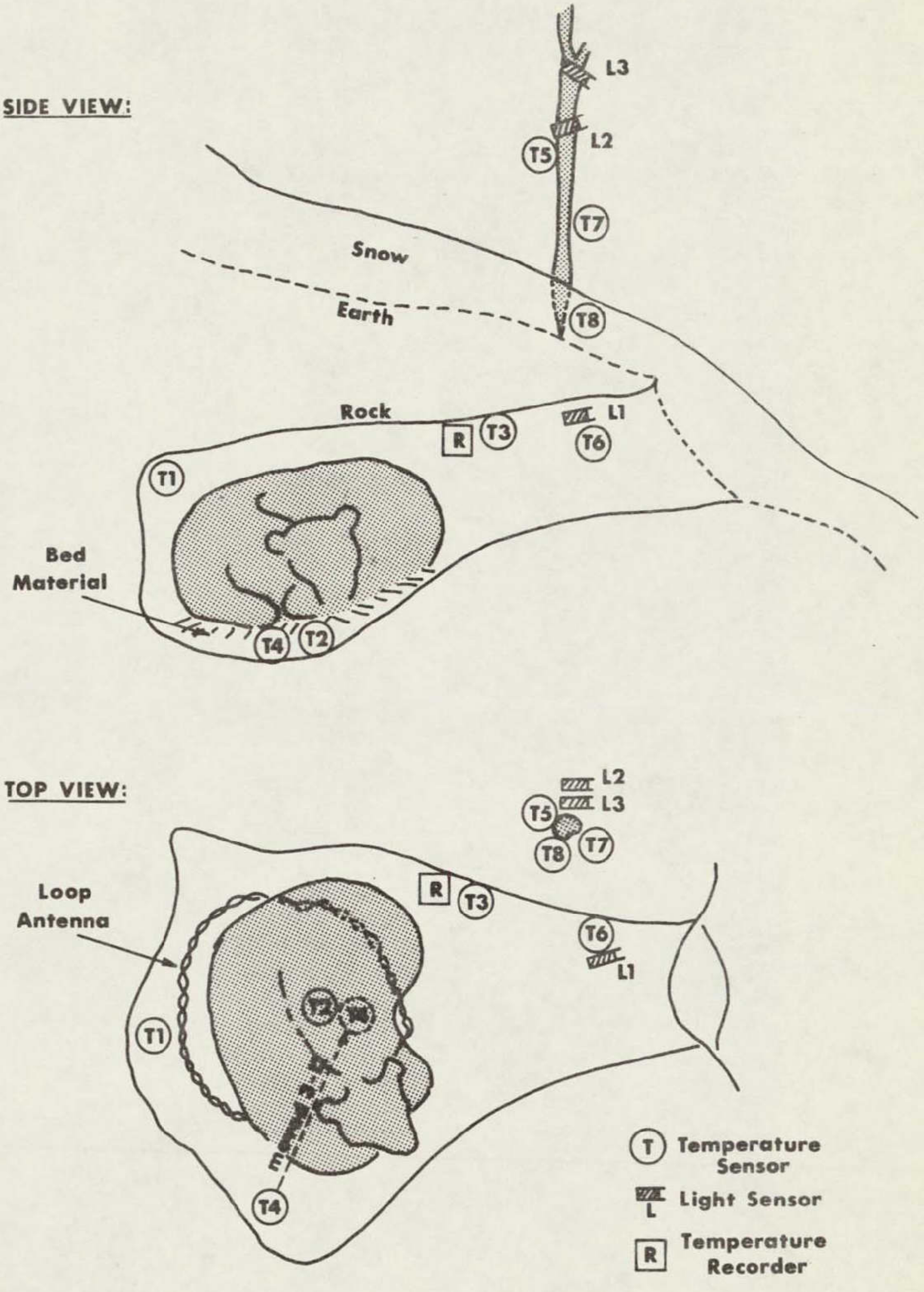


Figure 3: Placement of light and temperature sensors and recorders inside and outside the den. An additional temperature sensor and a temperature recorder were located further uphill from the the den and are not shown.

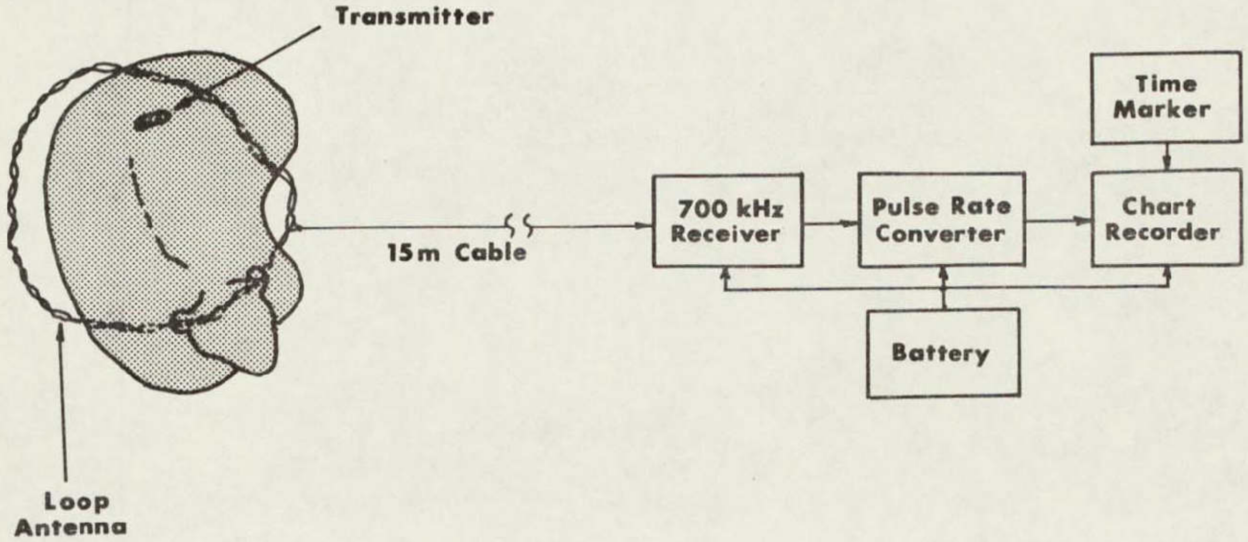


Figure 4: Block diagram of the body temperature recording system. Pulses from the temperature-sensitive transmitter in the bear were picked up by the loop antenna and recorded by equipment placed outside the den.

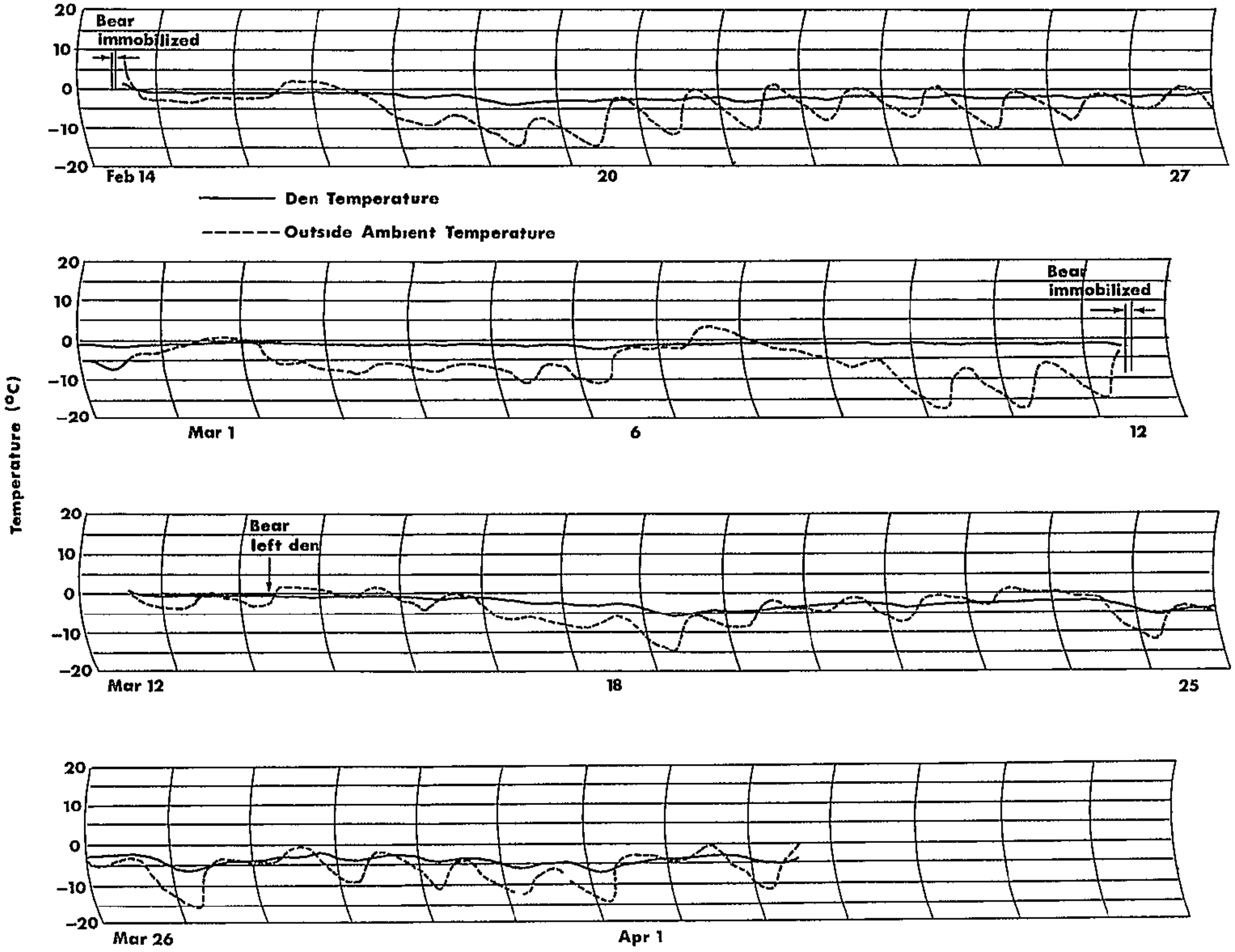


Figure 5 Continuous air temperature recordings inside and outside the den The inside temperature remained nearly constant near freezing while the bear was in the den After he left, den temperature decreased and was influenced more by outside temperatures

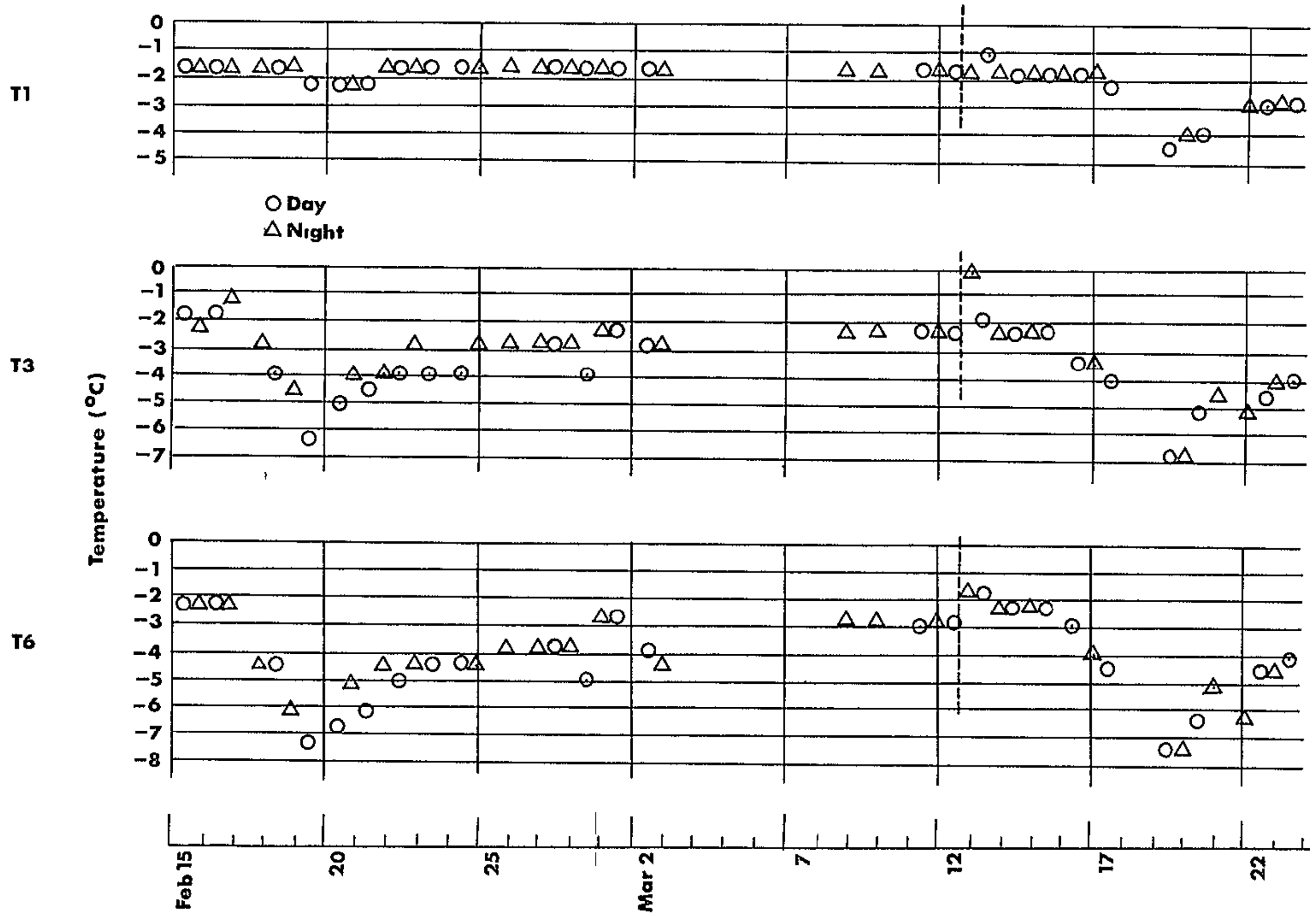


Figure 6 Satellite telemetry data for temperatures inside the den T1 was placed in the upper rear of the den, T3 halfway between the rear and the entrance, and T6 near the entrance The second immobilization of the bear is shown by the vertical dotted line

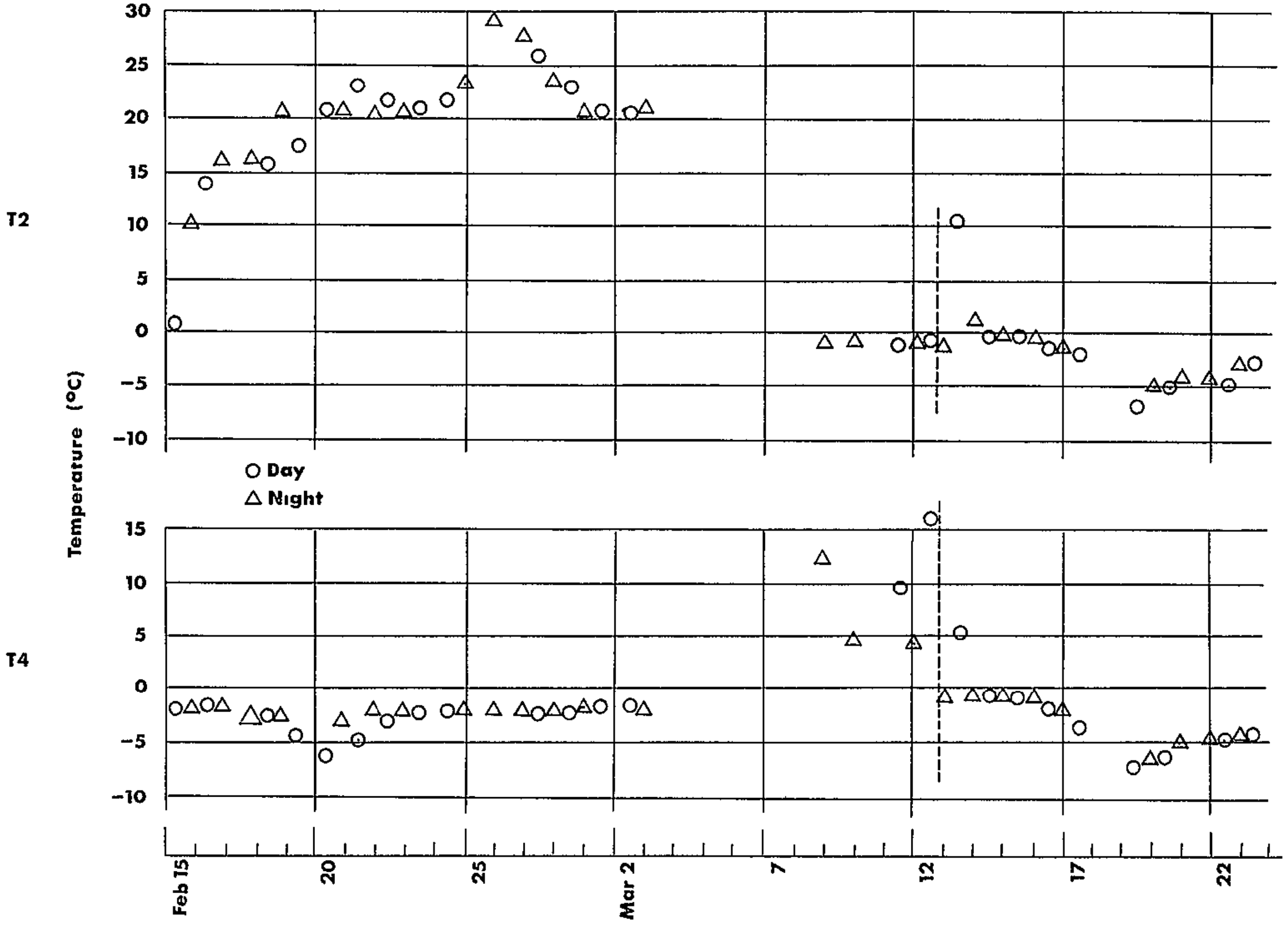


Figure 7 Satellite telemetry data for temperatures inside the den T2 was placed under the bed material on the den floor T4 was initially located near the floor on the left side of the den and was moved under the bed during the second visit to the den Considerable warming was caused by the bear's body heat

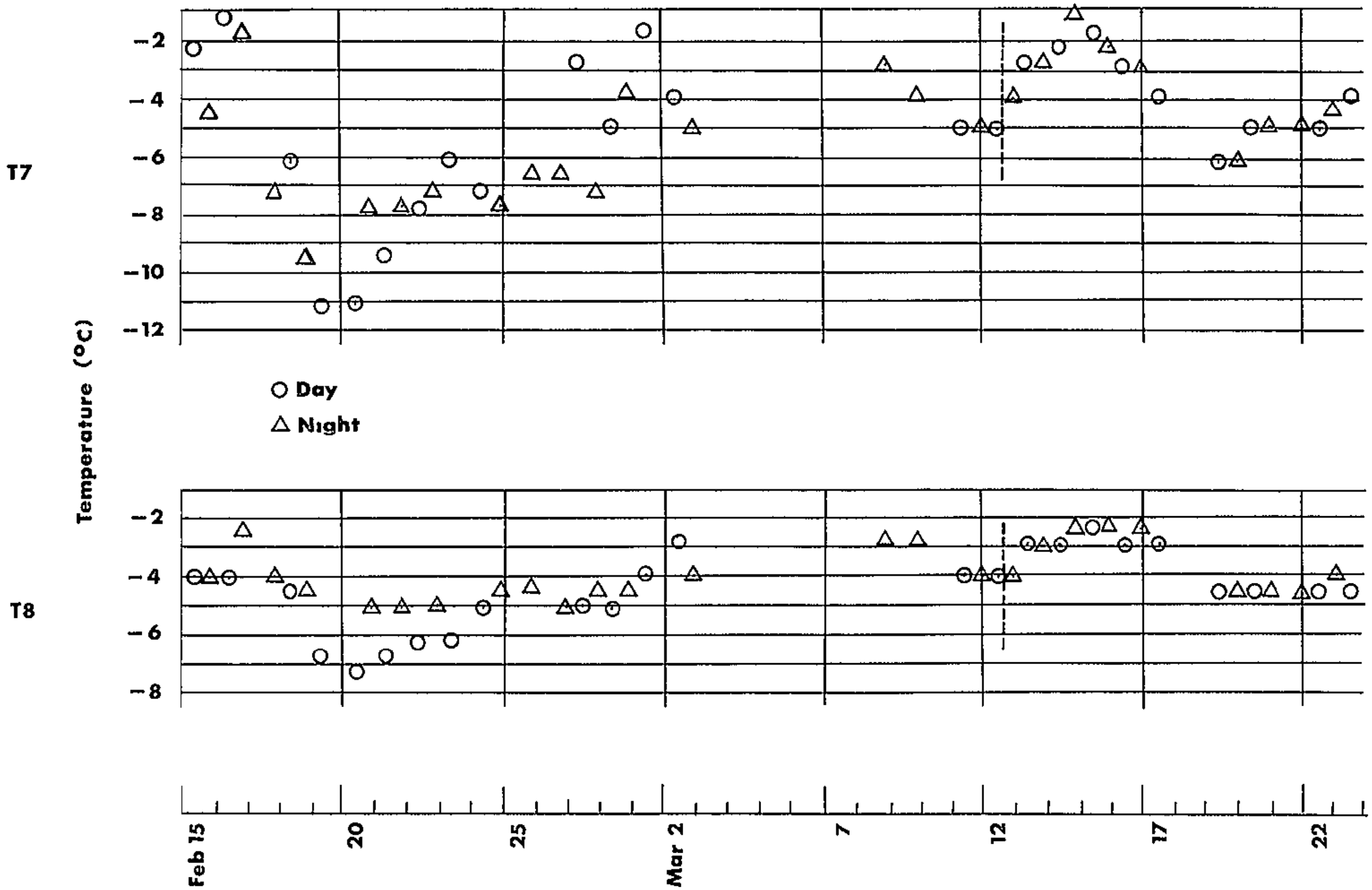


Figure 8 Satellite telemetry data for outside ambient temperatures near the entrance of the den T8 was placed beneath the snow T7 was initially 0 6 m above the surface but was later buried by additional snowfall

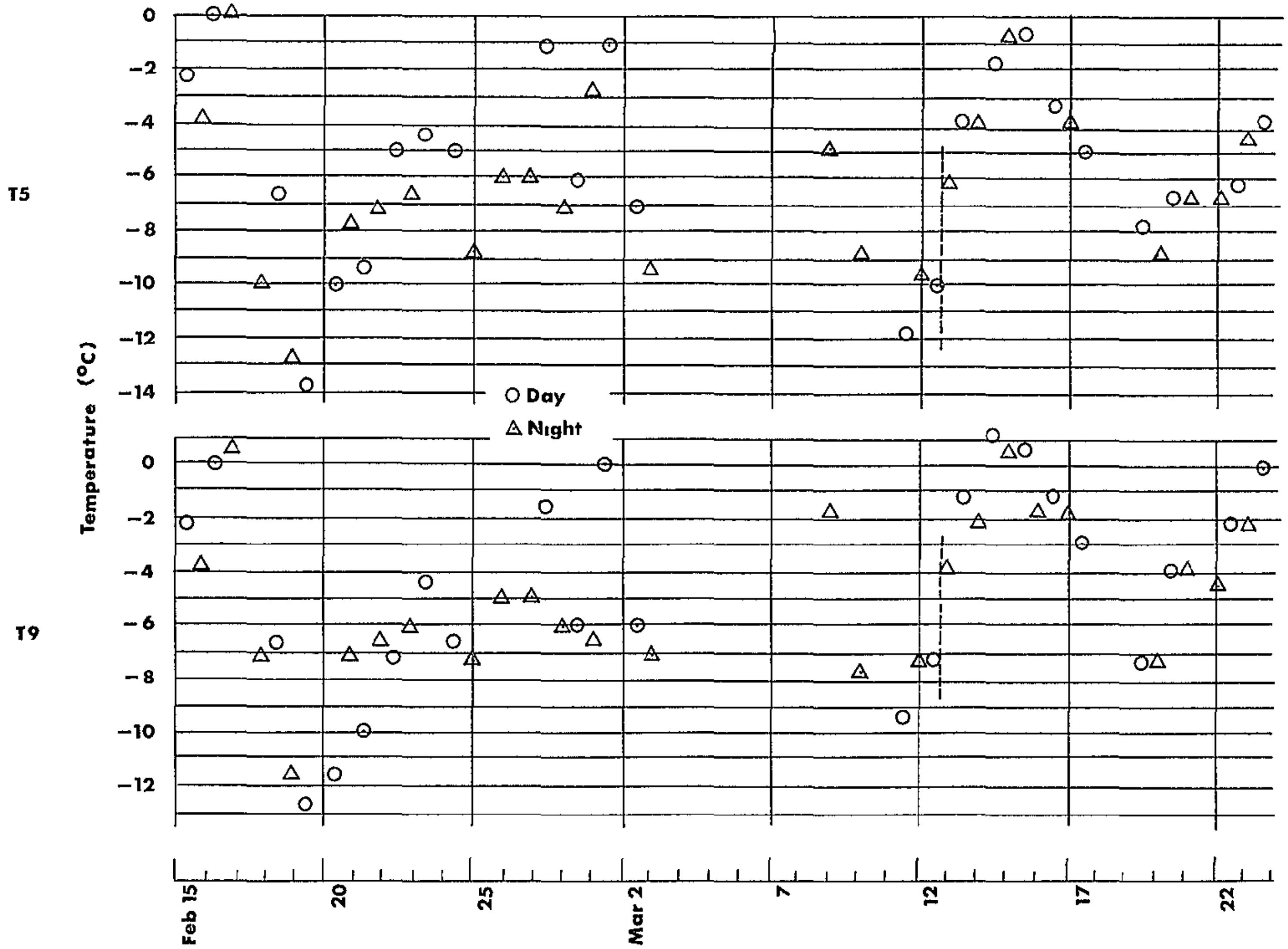


Figure 9 Satellite telemetry data for outside ambient temperature T5 was located 1 2 m above the snow near the den entrance T9 measured air temperature at the platform location 100 m uphill from the den

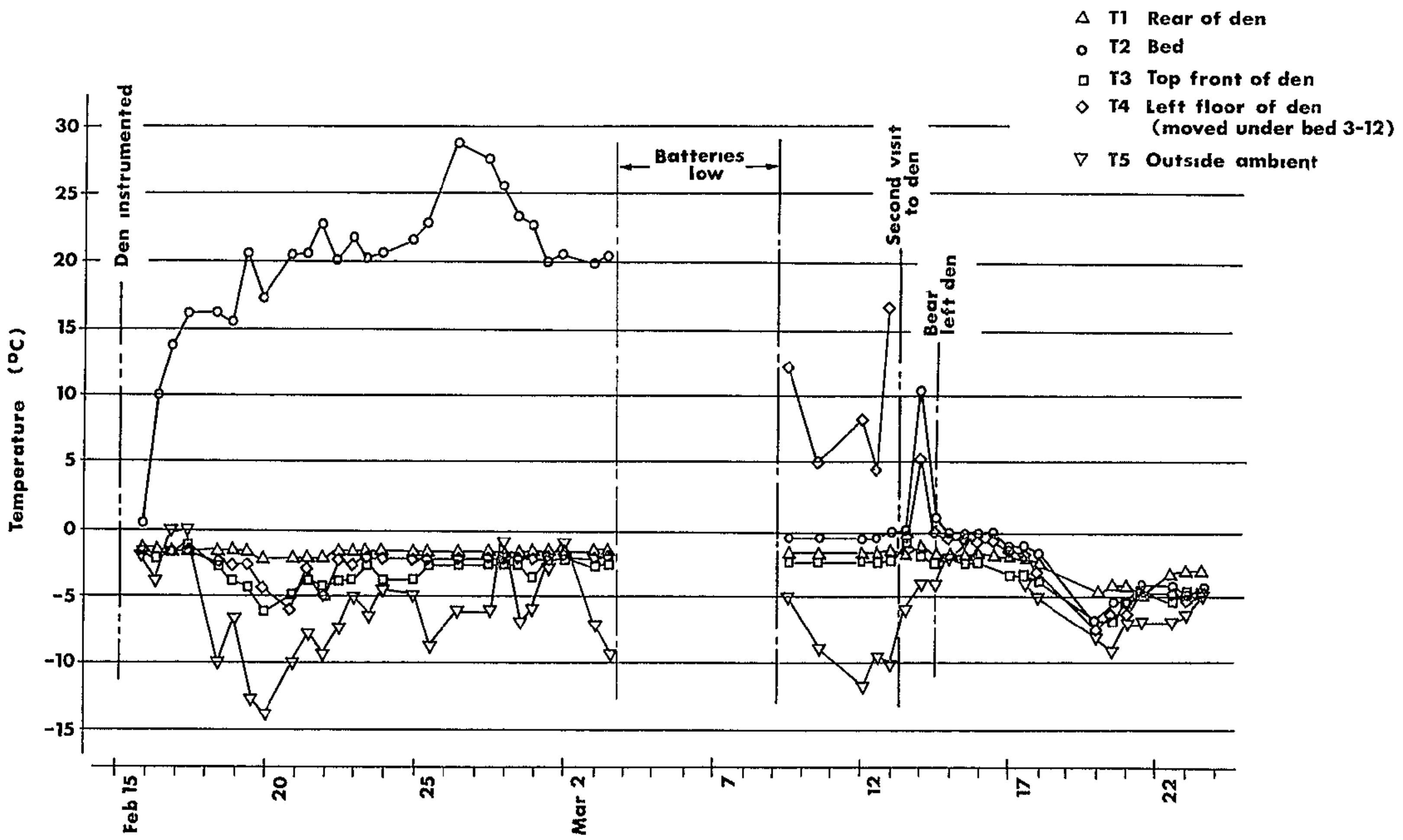


Figure 10 Comparison of temperature data from several sensors The decreasing effect of outside temperature on sensors located further from the den entrance is apparent, along with the influence of the bear's body heat on den bed and air temperature

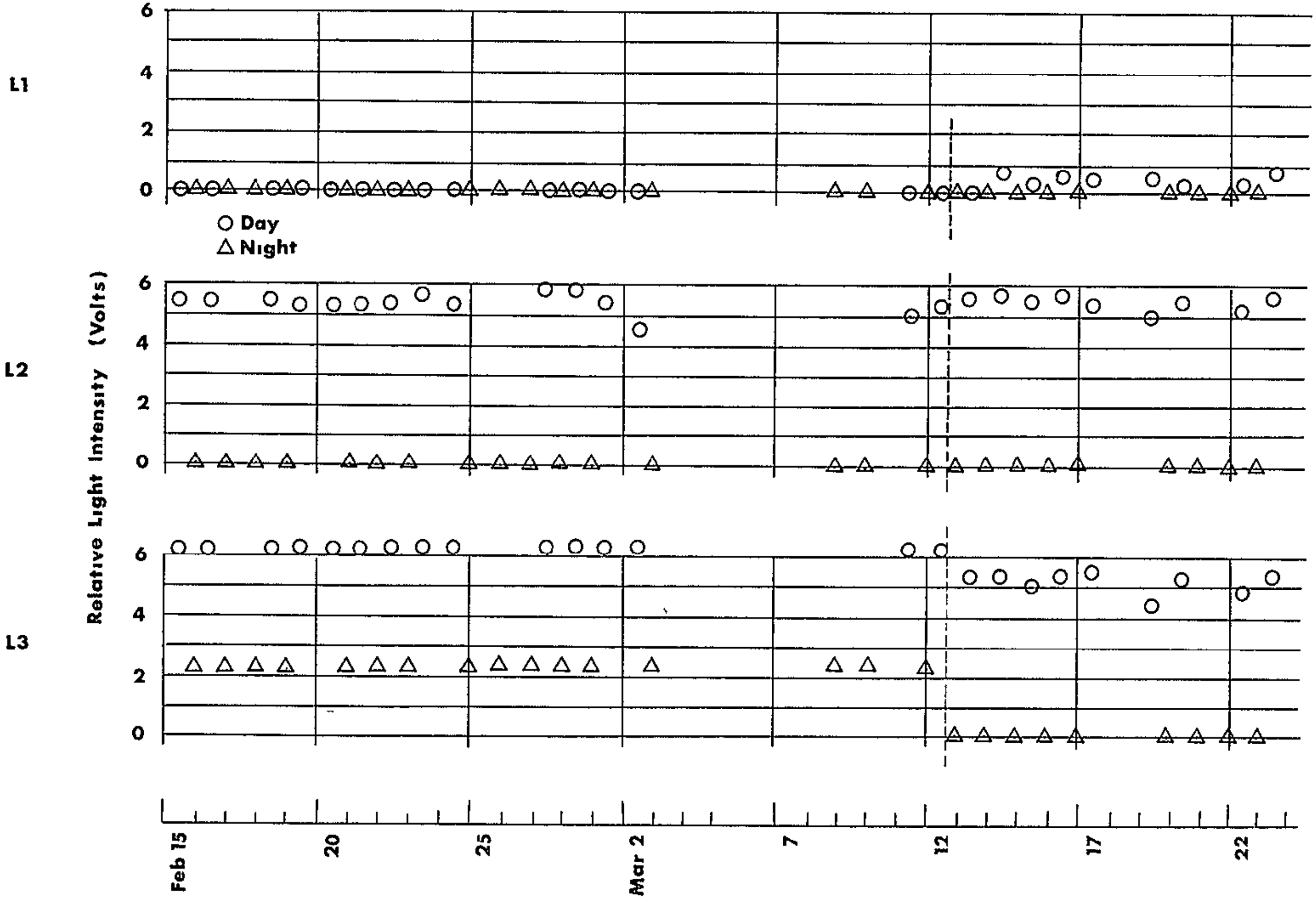


Figure 11 Satellite telemetry data for the light sensors L1 was located inside the den pointing towards the entrance, while L2 and L3 were outside

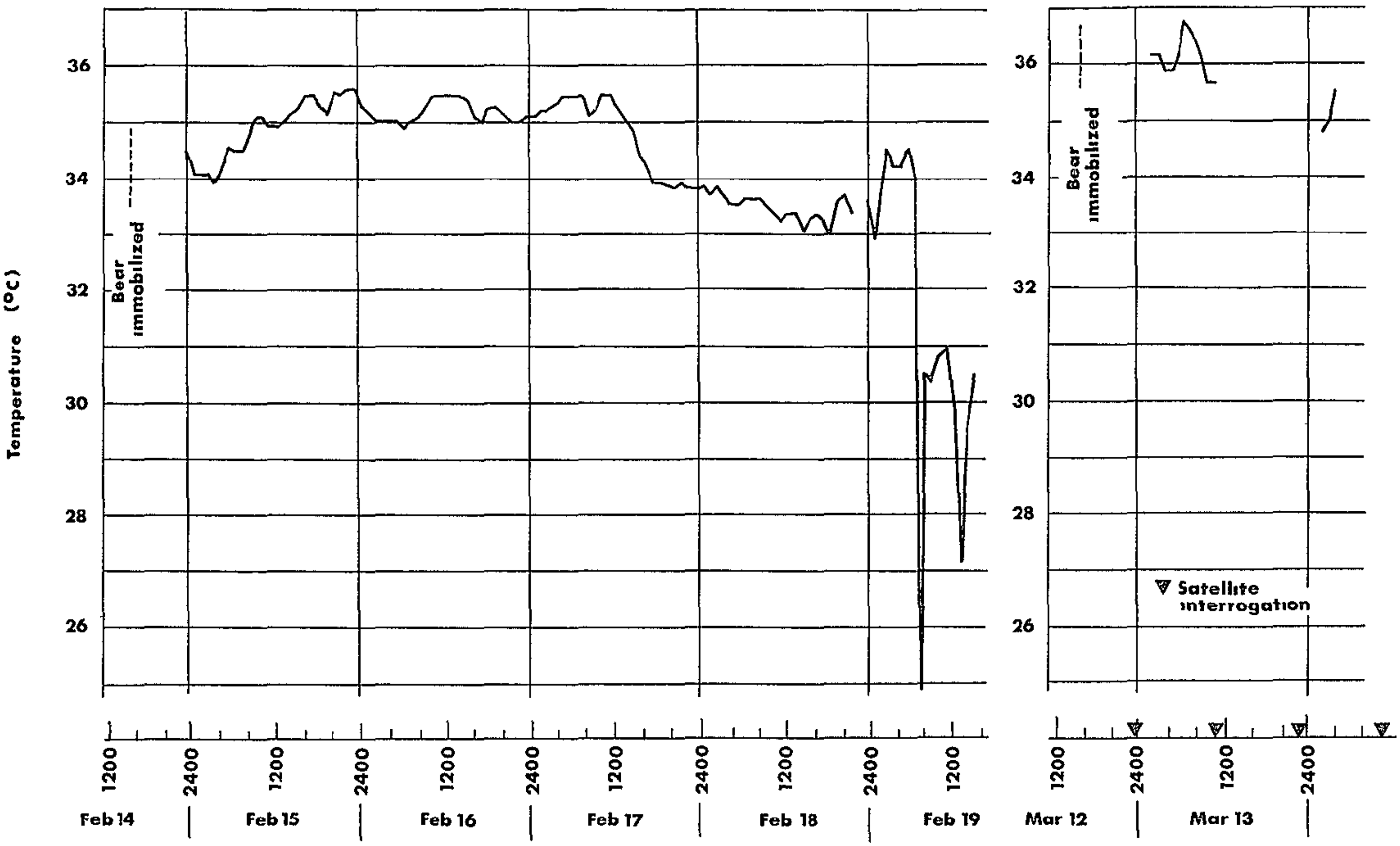
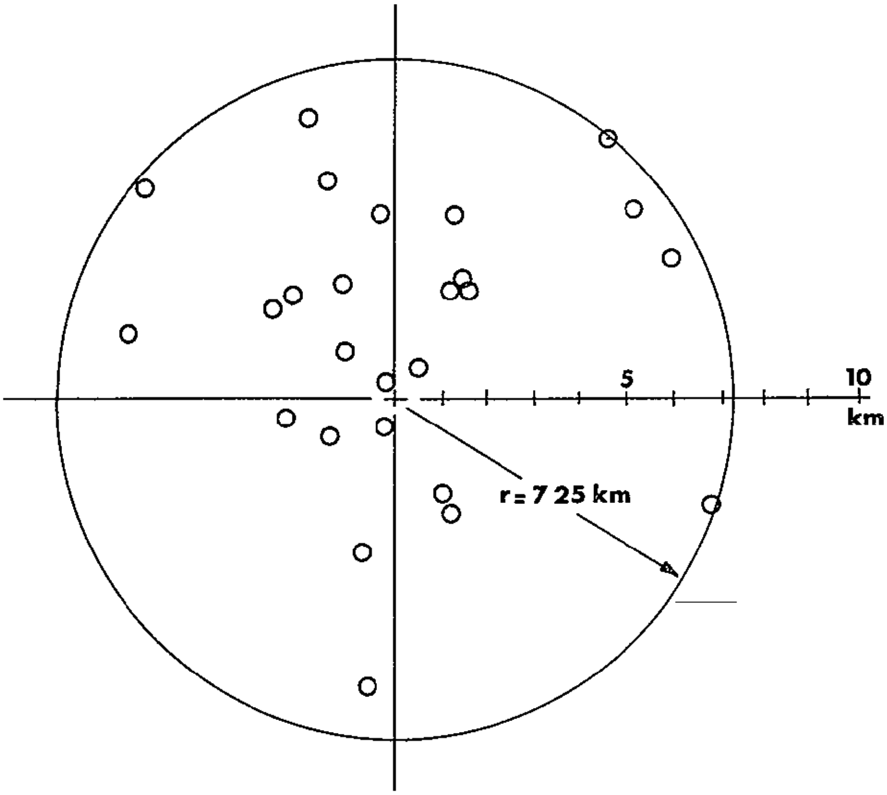


Figure 12 Temperature data telemetered from the rectally-placed transmitters Recordings were obtained for 4 days following the first immobilization and for portions of 2 days after the second



Average Error = 3 77 km

RMS Error = 4 31 km

Figure 13 Den locations computed from satellite data The known den location is the center of the circle

NOT REPRODUCIBLE

Plate 1: Black Bear (Ursus Americanus)

NOT REPRODUCIBLE

Plate 2: Fitting immobilized bear with a radio collar so that he may be tracked to his hibernation den

Plate 3: Moving equipment to the den area by oversnow vehicle

Plate 4:

Base camp near den

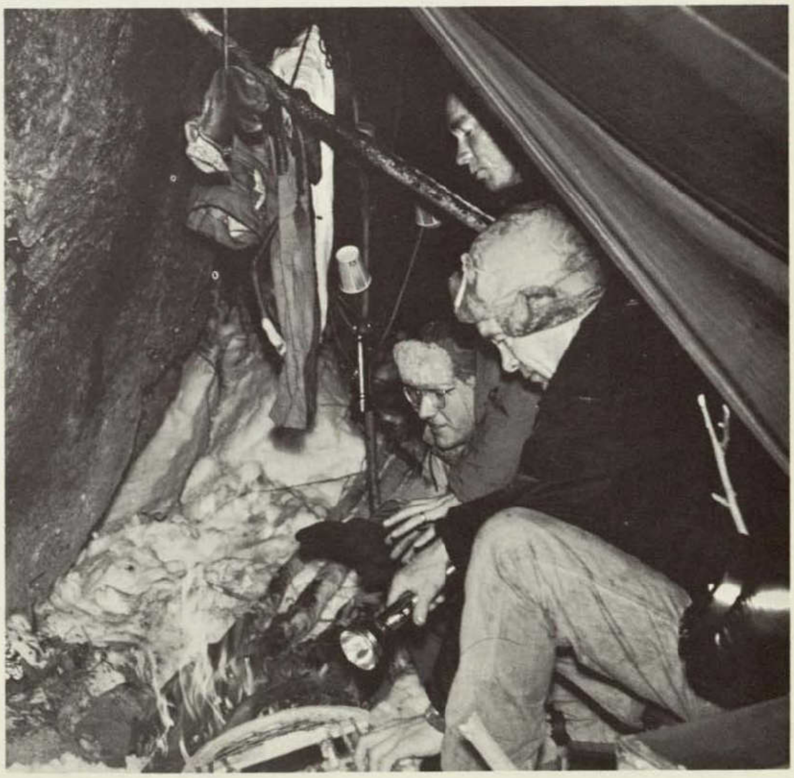


Plate 5: Black bear in hibernation den. The animal is in a state of hypothermia with a body temperature of 35.6° C (96° F).

NOT REPRODUCIBLE

Plate 6: Setting up the antenna for the satellite data collection equipment

Plate 7: Preparing to carry bear back to den after the immobilizing drug had taken effect

NOT REPRODUCIBLE

Plate 8:

Immobilized bear in front of den entrance

Plate 9:

Replacing immobilized bear in den after installation of sensors

NOT REPRODUCIBLE

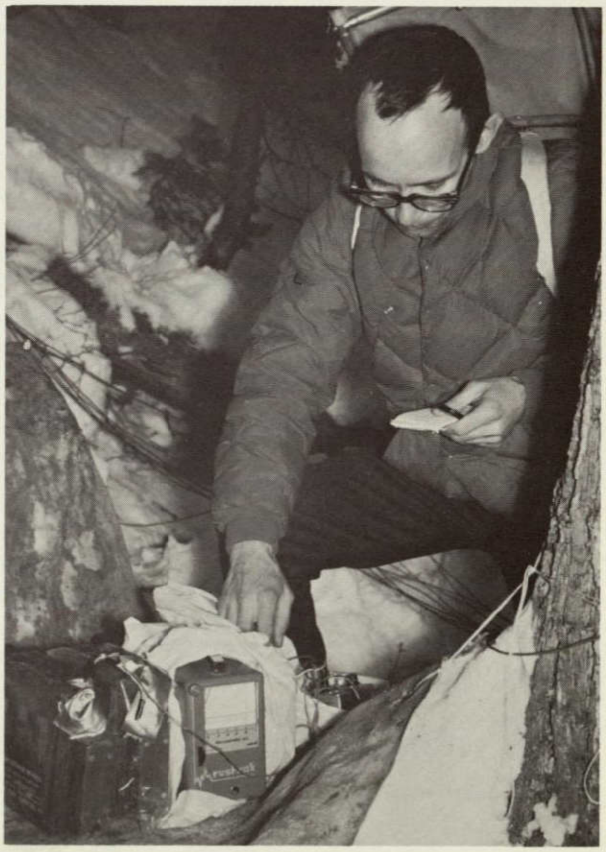


Plate 10:

On-site body temperature recording equipment outside den entrance. Data obtained from this equipment could be transmitted to the satellite.