State of the Art—A Review

JOHN H. BUSSER
American Institute of Biological Sciences

A LOOK AT THE SUBJECT MATTER of this symposium reveals a prime interest in three sets of information relating to the animals under investigation: Where are you? What are you doing? What's it like outside? It is from these data that the investigator hopes to deduce answers to his primary questions relating to How. . .? or Why. . .?

Instrumentation developed over the years to help answer some of these questions includes: transducers to sense the data of interest and convert it into something that can be handled and transmitted or stored; transmitters to send the data from one place—usually the animal—to another—usually the investigator; receivers to receive the data and convert it back into some form intelligible to the human senses, or suitable for storage; processors to render the data more suitable for the final step in the process—interpretation.

It would be possible to treat a review of this nature in a variety of ways. I shall restrict my approach here to looking at those methods and devices that are in current use in more than one isolated laboratory, unless something unique is of sufficient merit to warrant broader use.

Transducer classification will be by function rather than by the physical principle employed in the transduction. Two terms will be used that require explanation: passive and active transducers. Passive transducers require an additional source of energy to extract the information about the energy that you wish to measure. Active transducers convert one form of energy directly into another. Examples would be the thermistor which requires application of current to extract the temperature information and thermocouples which are in themselves sources of current related to their temperature.

The overriding considerations in all animal-borne transducers are size, weight, and power consumption. Secondary considerations are related to the ease with which a transducer can be matched to a data transmission link and the details of the circuitry that may be involved related to the accuracy or precision (or both) of the data required.

Time is usually inserted into the data at the recieving end of a given data link. The only real problem with time relates to the need for integration of data for (essentially) instantaneous transmission to a satellite or for storage. It will be impossible to unscramble, say, an integrated record of light level to determine when it was at a maximum.

Sound can provide much information but requires considerable channel bandwidth for its transmission. Using the same channel it would, for instance, be possible to transmit five or more pieces of information such as temperature, pressure, light level, etc., in the same "space" as one speech channel. Transducers for sound are sensitive to sound pressures from about 0 dB SPL up—(sound pressure level of 2×10^{-4} dynes/cm^2 RMS, which is roughly the threshold of normal binaural human hearing at about 2000 Hz). (See *Audio,* July, Aug., 1969 "A Primer on Sound Level Meters.")

Movement of any sort is accompanied by sounds or accelerations. A rule of thumb for acceleration transducer sensitivity is an output of 1 mv per "g" (982 cm/sec^2) per gram of transducer weight—with a lower limit of that weight being in the order of 2 grams (e.g. a 10-gm transducer would put out about 10 mv/g). It has been amply demonstrated that the observant investigator can quite often correlate other recorded variables with gross animal movements, relating changes in a radio frequency telemetered signal with wing beat, for example.

Position in three dimensions requires one angle and one distance to be measured, as with radar technique, or the less expensive triangulation with three angles from two known baselines. A variation on the latter employs the phase-lock receiver, which can achieve an accuracy of about $\pm$ 1° at 45° or about $\pm$ ¼° at 15°. At 1 km a $\pm$ 1° resolution means location accuracy to about $\pm$ 15 m in two dimensions. Using radar techniques it is quite possible to locate airborne targets to better than 10 times this precision and hence to an accuracy limited only by the accuracy of the original surveying of the instrument site. Radar technique is not the technique of choice for ground targets because of the response from all other matter surrounding the animal. This "ground clutter" will usually obscure any response from a surface animal. Using sonar techniques in water, it is possible to track an uninstrumented 1-kg animal over a range of ½ to 1 km with reasonable assurance that one has been following the same animal. Both of these techniques are treated more fully by other participants of this symposium.

Position over a short range, or within a confined area, may be obtained for an instrumented animal to a precision limited only by the complexity to which the experimenter is willing to go. By dividing the ground area into small areas and interrogating each in sequence, or by criss-crossing the area with "U" or "hairpin" antennas and determining which intersecting area is involved, it is possible to create a time-location diagram.

Direction of motion may be inferred from a series of position data; however, no detail may be read into such data. Actual animal headings, implying, for example, the compensation for cross-wind or current, must come from instrumentation carried by or intimately related to the animal. Such instrumentation is not yet available in light, compact form.

Cost of maintaining watch over a particular animal for a significant period of time during a migratory or other protracted voyage is high. As other members of this gathering will relate, aircraft of all kinds—fixed and rotary wing, free and powered balloons—have been employed at various times with varying success. It is not germane to enter here into the discussion of the influence of a following aircraft on the normal patterns of behavior of a bird, or of a following boat on the normal pattern of an aquatic animal, or of a following field vehicle or safari on the pattern of behavior of a land animal. Nor is it germane to do more than bring up the obvious that equipment mounted on (or in) any animal will affect its behavior in some way, and that we can probably relate fairly directly the effects on behavior of any abnormality perceptible to the animal. The corollary to this is that an instrumentation system must strive to have its animal-borne component be as insignificant to the animal as the ingenuity of the investigator can achieve—or pay for.

Environmental conditions that may influence behavior, or which may be used as clues to explain behavior include light, sound, temperature, pressure, and magnetic fields.

Light levels in the environment can be measured to a lower limit of the (usually) electrical "noise" in the instrumentation system, or the "dark current." This will tend to limit the usefulness of such transducers as the passive photoconductive diode to 10 ergs/cm^2 sec in an uncomplicated system suitable for animal-borne equipment. Of the various photodetectors available, the photoemissive tube would be of choice because of speed or response and stability if it were not for its large size, fragility of the evacuated or gas-filled glass envelope and the requirement for a relatively high voltage on its anode (45 to 200 V). Photovoltaic cells (active cells) may be totally adequate if the light level range is restricted to about 100:1 and the temperature range is less than $\pm 10°C$—or is independently measured for correcting purposes. The main disadvantage to the resistive photodiode is its relatively sluggish response to falling light levels and its "light memory," which restrict its usefulness to absolute measurements over a range of about 1000:1 in a temperature range of $\pm 10°C$.

Polarized light requires the addition of a filtering device and the ability to orient the device in known directions, or to know several specific orientations—to divide the universe into a few steps or many, depending upon the needs of the experiment.

Temperature transducers in this context have been empirically narrowed to the use of passive thermistors—devices that change their electrical resistance with temperature. They are small, light, and with reasonable care are more accurate than any other method. The precision available is also in excess of any but the most sophisticated (and hence complex) of other methods. Thermistors have the added advantage of often being usable as a circuit component in a conventional radio transmitter, with considerable saving in complexity and power use. Typical sensitivity achievable will be in the range of 3- to 5-percent resistance change per degree Celsius. Physical size ranges from a minimum of "pinhead" to 1 or more cubic centimeters.

Pressure of the atmosphere can be transduced as well as the transducer can be sealed. The transducer usually employs a diaphragm and a sealed chamber, with means for passively determining the diaphragm deflection using strain gages or by electrical inductance or capacitance changes. Since these latter can often be employed with minimum additional circuitry to directly affect a radio transmitter, they are often the method of choice. Typical sensitivity achievable with simple systems is 2 to 10 mm Hg. Pressure measurements within an animal employ similar techniques but include some means for equalizing the long-term ambient pressure changes to give only the short-term changes. Sensitivity will be in the same range, limited again by sealing techniques.

Magnetic fields remain somewhat of an enigma. Direction can be sensed by time-honored methods, but magnitude cannot. Transducers with outputs in the range of microvolts per gauss are not useful here but are representative of the state of the art.

Transmitters of position or other data that are attached to animals in the context of migratory or other long voyages that would appear to require orientation and navigation are usually radio. Over short distances light or sound sources, and over very short distances, atomic radiation sources have been used, and some of these are reported by others that follow in this symposium. In the main, however, the radio transmitter is the method of choice, and the theoretical limitations are well known and understood. Typical "thinking numbers" would include a minimum transmitter of about 10 grams to achieve an air to ground range of 5 km or a ground-to-ground range of ¼ km, with a useful life of 1 month. Additional life may be had at the expense of weight at the rate of about 10 grams per additional month required. Generalizations of this nature are very dangerous, since there are so many variables that enter into the solution to a given specific problem. By rigid optimal design 2 grams can be made to achieve what 20 grams might achieve under other circumstances in which some other boundary condition was limiting.

A review of progress over the last 8 to 10 years—since the last organized gathering of this nature—reveals that there are many more people who are using particularly radio telemetry techniques today to assist them in getting data from and about navigation and orientation functions in animals. The equipment itself is still very similar to that described at the meeting of March 1962 at the American Museum. Individual electronic parts have decreased in size to the point where the power supply and antenna size tend to be limiting. There is also still a dearth of commercial sources for completed equipment, so that much progress is slowed because of dependence upon empirical development by the wrong people. Signal processing, when needed, is under about the same constraints as the transmitter, in that, when the expense can be justified, integrated circuitry can achieve volume compression to about 0.25 cc per channel. There has not been any breakthrough development in transducers suitable for uses in this field, so that electrodes still cease to be effective after 3 to 6 months, pressure still requires about 0.2 cc for a transducer with about a 3-month life, and there is no immediate prospect of using subminiature ion sensing electrodes for studies of more than a few days duration.

One advance that has taken place is the development of a more successful sealing compound—a mixture of 100 parts paraffin wax (Atlantic Refining # 131) and 20 parts Elvax 260 (DuPont Co.). This has been shown to retain resistance to body moisture penetration over a 37 000-hour period in excess of 10^{13} ohms across about a 0.125-mm film. Its use under a surface protecting film of silicone rubber is recommended. Since the silicone rubber is permeable, a finished assembly may be chemically sterilized.

It would be very pleasant indeed if I could report more spectacular progress. Perhaps the discussion period will bring some out.

For those of you involved in the daily use of these techniques, I would recommend two books of recent vintage: Mackay's *Bio-Medical Telemetry: Sensing and Transmitting Biological Information from Animals and Man* (2nd Ed., Wiley, 1970) and Geddes and Baker's *Principles of Applied Biomedical Instrumentation.* (Wiley, 1968) There are others to which these two will lead you.