N72-25191

S57

SYMPOSIUM ON BIOTELEMETRY
PRETORIA 1971

Keynote address:

SENSING AND TRANSMITTING BIOLOGICAL INFORMATION FROM ANIMALS AND MAN

by

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BIO-MEDICAL TELEMETRY : SENSING AND TRANSMITTING BIOLOGICAL INFORMATION FROM ANIMALS AND MAN

by

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SYNOPSIS

Radio transmitters swallowed, surgically implanted or carried externally can be used to study animal and human subjects with minimum disturbance to normal activity patterns. They have been used to study freely swimming fish, porpoises and alligators, birds while flying, animals in burrows in the ground and fetuses in the uterus of conscious, active mothers. It is possible to sense and transmit a variety of kinds of information. Fundamental studies of humans whilst recovering from illness or whilst working in hazardous environment are possible by remote monitoring. Drugs can be tested with minimum effect from extraneous influences. Two extreme examples to be mentioned include tiny transmitters placed in the eye to record pressure changes produced by unexpected sights (in glaucoma studies) and the following of animal movements over great distances from artificial earth satellites.

Contributions have been made by many investigators and the possibilities are indeed numerous for workers in a wide variety of fields. Some of these will be indicated.

SINOPSIS

Radiosenders wat ingesluk, chirurgies ingeplant of uitwendig gedra word, kan gebruik word by die studie van visse, tornyne en alligators wat vrylik swem, voëls in vlug, diere in gate in die grond en fetusse in die uterus van aktiewe moeders by hul volle bewussyn. 'n Hele verskeidenheid gegewens kan op hierdie wyse bekom en oorgesend word. Fundamentele ondersoeke kan op mense uitgevoer word terwyl hulle van siekte herstel of in gevaarlike omgewings werk, deur van telemetrie gebruik te maak. Die uitwerking van artsenymiddels kan nagegaan word, met minimale beïnvloeding deur faktore van buite. Twee besonder noemenswaardige voorbeelde is die plasing van miniatuursenders in die oog om drukveranderinge te registreer wat ontstaan wanneer die pasient onverwags iets sien (by glaukoom-ondersoek) en die volging van dierebewegings op groot afstande met behulp van kunsmatige aardsatelliete.

Bydraes is reeds deur baie ondersoekers gelewer en daar is feitlik onbeperkte moontlikhede vir navorsers op 'n wye verskeidenheid gebiede. Enkele rigtings sal aangedui word.

KEYNOTE ADDRESS

SENSING AND TRANSMITTING BIOLOGICAL INFORMATION FROM ANIMALS AND MAN

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Radio transmitters swallowed, surgically implanted or carried externally allow the study of a subject with minimum disturbance to normal patterns of activity, and can allow study of otherwise inaccessible parts of the body. In many cases the most challenging aspect of the observation is the sensing of the physiological variable to be transmitted. A great variety of transmitter sizes and transmission ranges exists to fill the needs of the experiments to be undertaken. Examples of the extremes include the transmitter developed by Carter Collins in connection with his doctoral research, which units could be surgically implanted in the front chambers of the eyes of rabbits to continuously monitor pressure. All sensory modalities, including unexpected sights, produced a transient rise in pressure. These tiny passive transmitters need only carry their signals from inside to outside the eye to be effective. At the other extreme, H. Buechner, C. Cote and F. and J. Craighead have had an elk fitted with a 25 lb. collar, the animal's location being determined by an artificial earth satellite. We are presently attempting to develop a satellite method for monitoring the position and activities of flying birds in any part of the world.

Other transmitters have been used to study fish, porpoises and alligators freely swimming in ocean or fresh water, animals in burrows in the ground, fetuses in the uterus of conscious active mothers, monkeys in trees, etc. The signal from a small weak internal transmitter can be retransmitted to great distances by an external "booster" transmitter carried by the subject or placed in his normal vicinity. In a related application, an anesthetic dart fitted with a tiny short life transmitter can help find an animal fallen unconscious in the brush.

Humans can be monitored while recovering from illness or while working in a hazardous environment. As an example, by using these methods a convalescing patient can move about and yet be warned of irregularities of heart beat that make the taking of certain drugs necessary. In a hospital, it is becoming almost easier to monitor ECG or EEG by radio than by direct wire due to the avoidance of ground loop and noise pick up problems. Telemetry also largely eliminates electric shock hazard.

The radio frequency of transmission chosen will depend on the application, and will generally fall in the range of 50 kHz to 300 MHz. In other cases where information is to be collected rather than immediately acted upon, and where very small size and high data rate are not required, a recorder can instead be carried by the subject. The recorder can be made self-detaching for work with animal subjects. Short range position information can sometimes be obtained by the use of magnets or radioactivity rather than radio, and signals through ocean water are often best carried ultrasonically. In some cases optical telemetry can be done with a light emitting diode.

Internal placement of a transmitter not only eliminates leads that can tangle, pull loose or infect, but with uncooperative animal subjects it minimizes the possibilities for active destruction. With groups of animals, telemetry can supply a better estimate than observation alone of what is happening, and of social interaction. Intense activity with little meaning to the individuals may be associated with bluffing. On the other hand, since a direct look is a sign of aggression to many animals, a group can be sitting around looking in random directions, and an investigator with no physiological monitoring facility would have little clue that intense feelings were at work.

Frequency modulation is often used to superimpose information on the radio signal, and thus frequency recording equipment is often required at the receiver. One can also gain information about movement or activity and proximity to a given spot by suitably placing a receiver and then recording signal strength changes by attaching the speaker to a low speed penwriter through a diode. In connection with localization observations, it should be noted that a "near field" antenna can observe one region in space alone.

A few examples of experiments may prove helpful. In Fig. 1[**] is seen a radiograph of a snake (boa) that has swallowed a mouse containing a transmitter of pressure and temperature. The application was to a study of peristalsis in cold-blooded animals. Similar studies, without the mouse, can be routinely done on human subjects, for example, in testing or adjusting the dose of spasmolytic drugs. In Fig. 2 is seen the study of a human subject following the swallowing of one of these so-called endoradiosondes.

Such a transmitter is useful if its signal extends only a few meters. Even in the field, a single wire looped back and forth for reception can assure that a transmitter will never be far from this receiving antenna. The tiny loop systems from which the signal comes in these small transmitters are quite inefficient, the power emitted being only about 10^{-4} of that consumed. (The more powerful units in the later sections have antennas that are approximately 50% efficient.)

Swallowed transmitters have been used to monitor other parameters ranging from gastric juice pH to sounds, radiation intensity and temperature. In connection with the former, it is useful to note that field effect transistors can be incorporated into circuits displaying high enough input resistance to accept signals from glass electrodes. They can also function from microelectrodes used in single cell observations. With regard to nerve impulses, fewer acute experiments and more chronic studies seem needed, especially in young subjects where the system is still plastic.

In Fig. 3 is a radiograph of a rhesus monkey instrumented with transmitters placed in the body by surgery rather than introduced through a normal body opening. The four transmitters are simultaneously active on different frequencies, and transmissions that fill a cage are continuous for approximately a year. The upper two transmitters are for temperature and electrocardiogram. The next transmitter is an accelerometer to indicate motion or activity. The transducer associated with the bottom transmitter is placed on the outside of the abdominal aorta, and senses instantaneous blood pressure independent of changes in the elastic properties of the intervening vessel wall.

[**] The figures are placed in numerical order at the end of the text.

In other cases, several independent variables are telemetered from a single suitably placed transmitter, thus requiring only one battery and antenna. For example, in work with Ben Jackson and George Piasecki, three-channel vectorcardiogram transmitters are placed within the fetuses of sheep or dogs, which are later born with already functioning transmitters in them to allow monitoring before, during, and after birth. In Fig. 4 is seen the system for transmitting three independent voltages, and recording them through an ordinary entertainment receiver. The appearance of the transmitter, as soldered together using standard small commercial components, is seen in Fig. 5. On an oscilloscope each voltage can be displayed as a function of the others to yield three loops. Fig. 6 shows the progression of one of these three perpendicular loops over a period extending from before birth until the lamb grew too large for the electrode leads. In the fetus one sees the right ventricle being relatively equal to the left, compared to the later period when the left becomes stronger and dominates. In a fetus with pulmonary hypertension induced by tying the ductus arteriosis, the right ventricle appears to become dominant due to the pressure load. In these experiments the mother animal is observed going about her normal activities in another room over closed circuit television, while her fetus is being monitored *in utero*. Following the birth, she can again become pregnant.

In Fig. 7 is a photo of an external radio transmitter being used to monitor the electrocardiogram of a fish (a trout). This is from the Master's degree research of Matthew Weintraub on the effect of oxygen changes on heart rate. (Recording certain physiological parameters from a fish might allow local pollution monitoring in bodies of water, but this was simply a study of bradycardia.) The transmitter is a bit large in order to be neutrally buoyant, and the electrodes go between the pectoral fins and near the anus. Fig. 8 shows typical recordings in which both respiratory and heart signals, sometimes in synchronism, are seen. For clarity of explanation, the former are suppressed in the center tracing so ECG alone is seen. The circuit employed is rather like the bottom channel alone in Fig. 4.

By these few diverse examples, it is hoped that some of the possibilities are indicated. For further information and references, the reader may find Mackay, 1970, useful. To complete the presentation, detailed consideration of a single more powerful transmitting system will be given. It is intended for satellite work but has other applications as well.

The previously mentioned elk experiment used a transponder on the subject to indicate slant distance to the satellite (Fig. 9, top). From two successive such measurements the position of the subject is determined to be A or B. An alternative method using only a transmitter is indicated in Fig. 9, below. This Doppler method has some advantages and will be discussed.

Satellite Doppler Tracking Considerations

In the successful Transit satellite tracking system, a person on or near the ground can tell where he is by noting the frequency received from a fixed frequency transmitter in a passing satellite. The Doppler shift makes this frequency first appear a bit high and then low, and the rate of shift indicates how far to one side of the path the observer is. The inflection point in the frequency curve is obtained at the time of closest approach. Knowing the satellite position (orbit) allows determination of position, with the uncertainty as to which side of the path the observer is on being resolved by information from a previous "pass", or by the effect of the earth's rotation. Transmitter and receiver could be interchanged so that a receiver in the satellite could be used to determine the position of animals or other objects carrying fixed-frequency transmitters. In brief, the various parameters for a system to be used in monitoring the activities of large birds are determined as follows, the considerations also being instructive for many non-satellite applications.

In the range equation is a frequency term. In the present case the receiving antenna must "see" most of the earth from horizon to horizon. To avoid nulls its size will not be large with respect to a wavelength. The transmitting antenna must emit in all directions (an ideal to approximate), and thus the fraction of the total energy received will depend on the size of the receiving antenna. It will be larger and subtend a larger solid angle to intercept energy the lower is the frequency, and the necessary power thus decreases with the square of the frequency. (This is also true for an antenna working at a given frequency but physically reduced in size by loading.) The Doppler shift magnitude is proportional to the radio frequency, thus allowing a smaller bandwidth and less noise at low frequencies. This last may not hold if a suitable phaselock loop receiver is in the satellite. Thus, if the frequency is kept high enough for ionosphere penetration and adequate antenna size reduction, the necessary power can go down with the cube or square of the frequency. The frequency would be in the general range of 100-400 MHz, depending on what satellite is available.

The greater albatrosses, which are of interest, spend much of their time over ocean water which is an excellent reflector at these frequencies. The power received will cycle from approximately zero to almost four (not two) times the direct signal, and half the time it should be above the acceptable steady threshold. (The nulls and maxima, depending on sea state, are not quite as extreme as predicted; vertical polarization is slightly preferable in this respect.) For a 1000 km (600 mile) high (non-stationary) satellite, an albatross 0.1 mile high and a 100 MHz carrier frequency, the fading or beat frequency due to satellite motion between the direct and reflected wave for angles above the horizon from 20° - 70° goes from 0.25 Hz to 0.33 Hz. The maximum beat frequency is proportional to the height of the animal and to the radio frequency.

To determine a position requires three (or preferably more) frequency readings, preferably between 20° and 70°. To conserve battery power, the transmitter can be off most of the time, coming on for brief pulses at suitable intervals. (It can also be turned fully off at times when the satellite could not be near by using reed switches over the two hands of an Accutron timer with small magnets attached to the hands.) It should be noted that a satellite receiver logic that accepts a signal whenever available is also useful in dealing with aquatic mammals which transmit only while surfacing for a breath. From the above, an average estimate is that in the albatross case, half the measurements will be below threshold, requiring six measurements during a pass. A pass requires roughly four minutes. A pulsed system then requires a pulse at least every 40 seconds.

It will appear that a frequency accuracy of approximately one part in 100 million is of interest. A number of frequency measuring methods are equivalent to counting cycles and thus at a frequency of 100 MHz, 10^8 cycles implies 1 second pulses of radio energy. Thus one expects the transmitter must be on at least 1 second in 40 or 2.5% of the time.

Representative values of errors can be indicated. If E is the fractional error in the Doppler slope, then a simplified view is:

$$\text{slant range at closest approach} = \frac{\text{transmitter frequency}}{\text{velocity of radio}} \frac{(\text{satellite velocity})^2}{\text{max. Doppler rate }(1+E)}$$

Thus the fractional error in slant range equals E. A typical (not worst) case of a 45° satellite pass with a 1000 mile slant range or distance from closest point of approximately 700 miles requires a frequency stability during the pass of 2×10^{-8} for an error of one mile. Random noise in the frequency (not steady drift) of 0.5 Hz at 100 MHz will typically give an error of under 0.3 mile when the satellite passes at least 14° to the side of vertical. Refraction of radio signals causes negligible error above 500 MHz, but can give a 2.3 mile (2 nautical miles) error with a 400 mile high satellite and ground range of 500 miles at 200 MHz, and 8 miles at 100 MHz. If the bird moves parallel to the satellite's track a perpendicular error is introduced and if rapid movement is perpendicular to the path then there is a parallel error. From the equations of Guier (1966) one can consider a bird that travels 150 miles in 10 hours. The error in position due to a 15 knot speed would be cross track of about 2 miles if the angle of satellite elevation at closest approach was 45° and the velocity were parallel, or about 0.5 mile if the bird moved perpendicular to the track of the satellite. Altitude changes also exert an effect. Such errors are generally independent and add in square root fashion, but in the worst case their extreme values could all happen to sum directly; a satellite pass directly overhead obviously leads to decreased accuracy because of the geometry. With uncertainties of a few miles being likely, an oscillator stability of 1 part in 10^8 seems a desirable goal. The frequency should be maintained thus during the time of a pass near any one point, but it can drift somewhat during longer periods "out of sight".

Power and battery requirements can be estimated. For a signal/noise ratio of 10 db, a wavelength of 3 m (100 MHz), a slant range of 2000 miles, 50% loss due to antenna polarization, a bandwidth of 2300 Hz, and an effective temperature of the background of 290°K, the isotropically radiated power would have to be 42 milliwatts. Satellite experience suggests a more realistic temperature for inclusion is 2900°, thus requiring 420 milliwatts. If a phaselock loop receiver allowed bandwidth reduction to 10 Hz, power could be reduced by a factor of 200. A convenient order of magnitude for this narrow band system is to require 0.1 watt from an antenna, radiated as close to isotropically as possible. (It is difficult to build an antenna carryable by a bird that directs all power into the upward hemisphere over the subject.)

If the antenna is 50% efficient, the elctronics 60% efficient, and 100 milliwatts is required, then the battery power is 330 milliwatts. Mercury batteries, which give a relatively constant voltage, have a power density up to approximately 45 watt-hours/lb. A greater albatross can probably carry up to a pound. If the circuit plus packaging and antenna weigh 3 oz, then 13 oz of batteries could provide 37 watt hours. This would give continuous operation for 112 hours. However, if the transmitter were on for 1 second and off for 29, the life would be 3360 hours or 4.6 months. (Solar cells might supplement this if they did not become covered with dirt, feathers, and salt crystals.) Suitable battery types might be two TR-236R or six TR-167R or four TR-137R.

A low power relatively stable oscillator has evolved as at the top of Fig.10. It employs an AT cut fifth overtone crystal cut within a quarter minute of arc at approximately 100 MHz. It is a standard item having a temperature coefficient of 30 ppm over -30° to +60°C. The Colpitts-like circuit incorporating it draws 0.5 ma at 9.4 volt, while delivering 1.2 milliwatts into 27 ohms, for an overall efficiency of 25%. The use of a voltage greater than one or two cells in series reduces transistor capacitance and thus minimizes frequency shifts. An impedance mismatch to the output stage decouples the oscillator from changes in loading (e.g., wing movement near an antenna that can cause frequency shifts).

The temperature sensitivity of the oscillator is compensated by the thermistor in a way that allows adjustment without a computer, the method being similar and simpler than that of Vovelle (1968). Across the resistor below the thermistor appears a voltage that changes with temperature (in an unspecified nonlinear way). As it increases, the resistors associated with the three transistors successively are connected in parallel to modify the way in which this control voltage changes with temperature. This voltage is applied to the voltage-controlled capacitor (varactor diode) that slightly modifies the oscillator frequency. The resistors marked "R" are selected to compensate a given circuit, and are adjusted so that as temperature increases and frequency drops to a specified value, a resistor switches in to start the frequency rising again. The graph shows what can be achieved, the frequency shift from 0°-30° being 40 Hz and the worst temperature coefficient being 4 Hz/C°. This oscillator package is 2.5 x 2 x 1 cm and weighs 4.3 g, of which 0.6 g is aluminum shield and 0.6 g is rigid substrate.

The oscillator itself, using a Motorola MT 807 transistor showed a frequency shift of 1 in 10^8 for a 10% voltage change, but the same network can be selected to compensate for voltage as well as temperature changes if a voltage regulator would be needed. The controlling diode (1N5139 of TRW) is biased forward by 0.5 volt, which gives enough control range if the less effective MT2060 transistor (Fairchild) is employed. Shunting the crystal with C=4.5 pf returned the effect of the varactor. Inductors by Delevan are convenient.

The compensation cuts the range of absolute frequency changes, but one wants the incremental slope at every point to be low also. In conjunction with this, a goal is 0.1°C change in the oscillator package in 10 minutes for a 10°C outside change. This requires a thermal time constant of 1000 minutes. This is achieved by placing the thermal mass at the center of a thermal insulator. If the package is spherical, one can show that the radius of the central conductor should be about 2/3 the radius of the sphere containing an outer layer of insulation, and adding more of the latter helps little. An outer heat shield can also be helpful.

We have noted wax to be a valuable material, being one of the few simply formed things impermeable to body fluids, showing low tissue reaction and fairly low electrical loss at radio frequencies. Paraffin also has a high specific heat of 0.69. It has low thermal diffusivity and beeswax is better (10^{-3} vs. $2x10^{-4}$). However, oscillators potted directly in paraffin were unreliable because of parts shifting in response to the expansion of the wax.

It is necessary to slow any thermal transient, not just delay it. In terms of the overall system, it seems best to place the mass of the batteries around the oscillator and enclose that combination in a light insulator such as Freon foamed polyurethane (a better insulator than air blown polystyrene). The oscillator parts can be coated with polystyrene for minimum loss, under the aluminum shield. A little compressible foam around the shield can relieve stress from the surrounding paraffin, which can be loaded with 20% of aluminum powder so the central part will be more of a thermal conductor. The wires running from the oscillator must be long and fine so as not to conduct heat in directly. A small vacuum bottle we constructed was not as effective because of radiation.

One could use the transistor inefficiency to temperature regulate the crystal by having two power amplifiers contributing to the output. The temperature error signal would shunt the signal more or less to an outside amplifier rather than to the one near the crystal. Placing the crystal against the bird for temperature regulation is somewhat upset by bathing,rain, etc.

If the transmitter is to be turned on and off in pulses, the oscillator can be kept running and the output stage, where most of the power goes, can be switched. The present oscillator was tested under conditions where it was turned off in its entirety. The power was switched on in one microsecond. Amplitude built up for 10 microseconds, and some amplitude fluctuation was observed at 2 milliseconds. The frequency was constant after 100 microseconds, that is, the on-off mode had the same stability as continuous running, if the first 100 microseconds were ignored, which many receiver systems would do in the process of acquisition.

Physiological information can be superimposed on the oscillator signal. FM-AM modulation can be used, or the spacing between pulses can be varied to send slowly changing, averaged, or preprocessed information. Other transmission systems can be considered. For example, 100 microsecond bursts of radio frequency spaced digitally at 1 second intervals could have their period measured accurately at the satellite to yield Doppler information.

The signal from the oscillator unit can go directly to an antenna, or be further amplified. At the bottom of Fig.10 is shown an amplifier containing a frequency doubler followed by an output stage. It yields 200 milliwatts into a 51 ohm load with little harmonic distortion at 200 MHz with an efficiency of 60%.

This circuit was tested with several antennas. They were connected to the output of the 200 MHz circuit and the signal monitored with a field-strength meter. Agreement with expectations was within 10%. Tested were a half-wave dipole, a quarter-wave "whip" over a small copper plane, a tuned horizontal loop over a ground plane, and a directional discontinuity ring radiator. The dipole and whip were most efficient, with the other two giving somewhat less than the desired field strength.

In observations with two albatrosses, neither showed interest in a vertical wire from a pack on their back. It may eventually be desirable to explore the possibility of using the pack attachments as an antenna with mixed polarization, but somewhat resembling a "turnstile" antenna.

Harness Considerations

In the case of the bird, it is essential that the attachment of the transmitter package not interfere with flight, walking, swimming and eating or other movement. It is also desirable that the package eventually automatically drop away when the experiment is completed. A requirement similar to the latter exists, for example, if a self-detaching buoyant recoverable recorder is used to take physiological information from a freeswimming marine mammal rather than employing a limited range telemetry system. An iron wire link in a harness can rust away but there are more precise methods for accomplishing the result.

In developing a harness configuration, observations were made on pelicans, pigeons, and albatrosses, and extensive flight tests made with homing pigeons. For short term studies many attachments are useful, but the final design for this purpose combined rigid and flexible members. The latter were of plastic tubing, with stiffening supplied in some regions by metal wire (Fig. 11). From the back assembly (20 cm x 5 cm for a blackfoot albatross) the rigid metal guides (about 5 cm long) inside the tubing direct the front strap forward and slightly downward toward the shoulders away from both the neck and the wing. The strap is flexible across the shoulders for about 7 cm. A rigid metal "U" directs the strap from the carina up toward the neck to prevent it from slipping out to the wing joint. The shape of an albatross is such that the neck strap does not slip onto the wing when the metal "U" is omitted, but on a pigeon this support is essential. Placement on a blackfoot albatross for over a month with the tail loop in front of the legs worked (Fig. 12, taken before he had a chance to preen the harness down into the feathers), but from other tests it seems slightly preferable to have the back loop behind the legs, and angling forward. The straps are connected by two short cords which lie to each side of the ridge of the carina. Two strips of foam Neoprene rubber were glued along the back unit to prevent rubbing on the spine, and a bump in the "U" minimized rubbing on the carina.

The release mechanism should not damage the animal, and is perhaps more reliable if it does not require a large current surge late in the overall process. An irregular release should not cause a bird to fall if in flight. Negligible voltage and gasing are involved in plating cells (Mackay 1970, 1971), but dendrites can bridge the electrodes to stop all action, making controlled "corrosion" or electrolytic action preferable in some geometries. When the main battery is depleted, the cutoff bias is removed from the field effect transistor (Fig. 13) thus electrically connecting the dissimilar metals. The non-powered systems are still being studied, but reasonably pure aluminum, magnesium, or zinc all seem able to function as the supporting wire, in some cases because of formation of a passive film. The action can be confined to a small region for rapidity by coating other regions with insulating plastic rather than by adjusting the geometry. The effect of marine fouling has not been studied, but if the ocean water is the electrolyte, breaking will tend to occur when the albatross is on the water.

Acknowledgments

Technical contributions to these projects have been made by George Rubissow, Barbara Dengler, and Mark Abel. The harness tests on blackfoot albatrosses were made at Marineland in Los Angeles through the courtesy of John Prescott. Measurements of the greater albatrosses were made with the help of the bird banding group near Sydney, through the courtesy of Dr. William Dawbin. The studies on fetal life are supported by a grant from the John Hartford Foundation of New York, and the satellite studies are supported by NASA Grant NGr 22-004-024.

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Legends for Figures

Fig. 1. Radiograph of boa after swallowing a mouse containing a radio transmitter of pressure and temperature. The transmitter passed in the usual way, still transmitting, three weeks later.

Fig. 2. Monitoring peristalsis in a human subject during motion sickness induced by swinging while blindfolded. Note receiving loop antenna draped diagonally over one shoulder.

Fig. 3. Transmitters of four variables simultaneously active on different frequencies within the body of a rhesus monkey.

Fig. 4. System for transmission of three independent voltages from a single transmitter. Two nonsinusoidal subcarrier oscillators are employed, plus one channel of frequency modulation. The circuit is similar to one discussed by Mackay (1970), but is modulated by a voltage-controlled capacitor diode in a way that produces less distortion and allows greater output.

Fig. 5. Circuit of Fig. 4 compared with a centimeter scale when wired from standard components and encapsulated in epoxy.

Fig. 6. Transverse vector loop of the fetus of a sheep from approximately a month before birth until two weeks after. The other two loops can similarly be displayed using the system of Fig. 4. The oscilloscope trace is interrupted at a 1 kHz rate and the resulting dots blunted in the direction of progression of the trace.

Fig. 7. A trout carrying a neutrally buoyant radio transmitter on his back for recording electrical activity near the heart.

Fig. 8. Signals recorded under the conditions of Fig. 7 showing activity associated with both heart beat and respiration.

Fig. 9. Two methods for determining the position of a subject by an artificial earth satellite. At the top a transponder allows a series of range measurements in a wideband system requiring continuous activation of a receiver on the subject whenever the satellite might be near. Below is the Doppler system in which a transmitter alone is placed on the subject. From the slope and inflection point of the recorded frequency curve, the position of the subject can be determined, again with a resolvable ambiguity as to which side of the satellite track the subject is on.

Legends for Figures (continued)

Fig. 10. Top: A relatively stable low power oscillator, with output stage, operating in the 100 MHz region. Resistors labelled R are readily experimentally adjusted to compensate any given circuit.

Right: Degree of temperature stability possible in the circuit tested. Not shown is approximately 20 Hz hysteresis for a temperature change of 20°C since such drift has little effect on the present application.

Bottom: Output stage containing a frequency doubler to provide greater power at 200 MHz. Construction is on a copper sheet.
L_1 is 6 turns #20 wire, 3/16" I.D.
L_2 is 5 turns #20 wire, 3/16" I.D.
Power supply tap 2 turns from collector.
Output tap 3 turns from collector.
L_3 is 8 turns #22 gauge wire, 3/16" I.D.

Fig. 11. Bird harness for extended experiments with rigid elements appearing dark inside the flexible plastic tubing.

Fig. 12. One alternative placement of the harness on a blackfoot albatross, before there has been time to preen it down into the feathers.

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Fig. 2. Monitoring peristalsis in a human subject during motion sickness induced by swinging while blindfolded. Note receiving loop antenna draped diagonally over one shoulder.

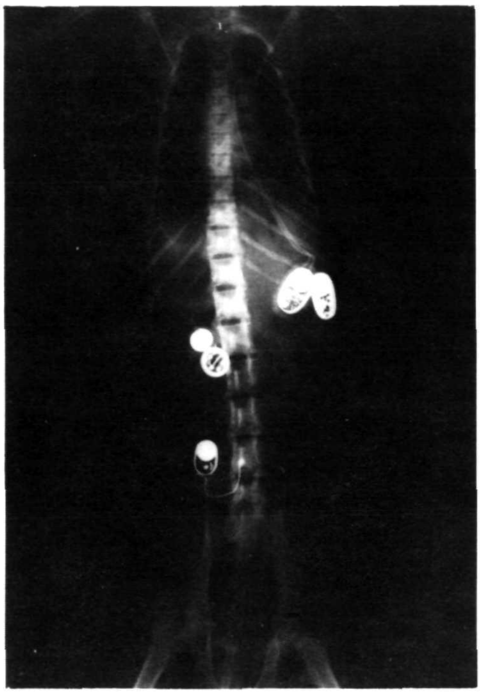
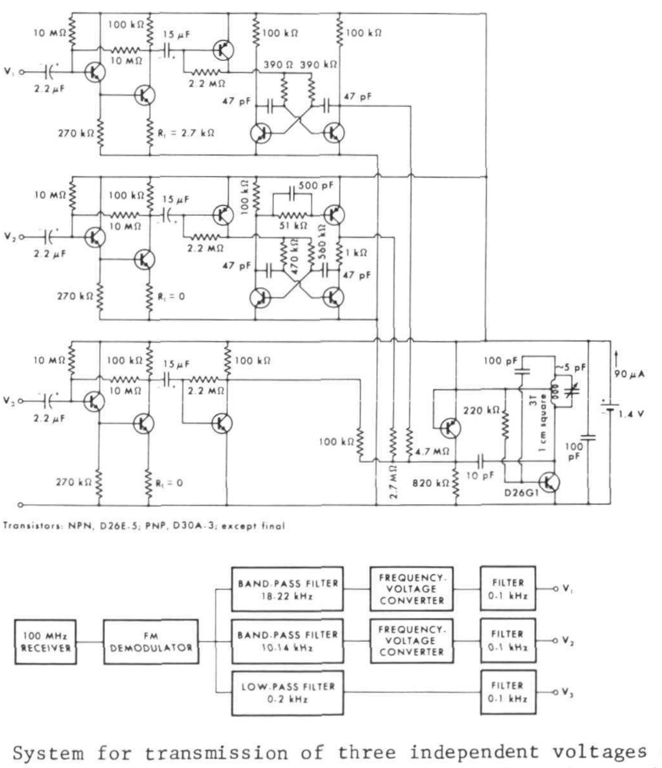


Fig. 3. Transmitters of four variables simultaneously active on different frequencies within the body of a rhesus monkey.



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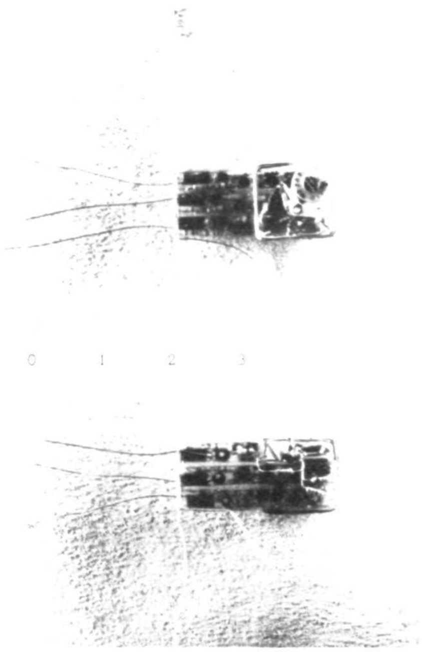

Fig. 5. Circuit of Fig. 4 compared with a centimeter scale when wired from standard components and encapsulated in epoxy.

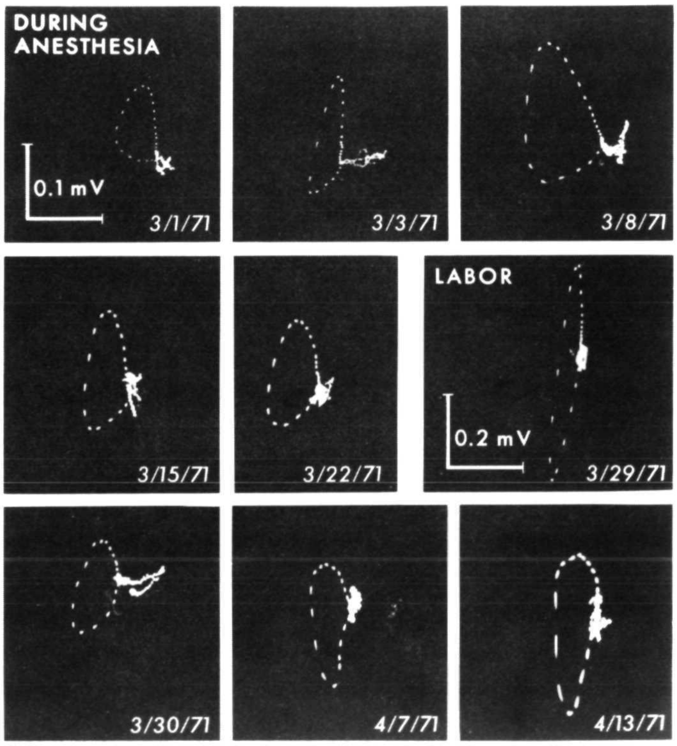

Fig. 6. Transverse vector loop of the fetus of a sheep from approximately a month before birth until two weeks after. The other two loops can similarly be displayed using the system of Fig. 4. The oscilloscope trace is interrupted at a 1 kHz rate and the resulting dots blunted in the direction of progression of the trace.

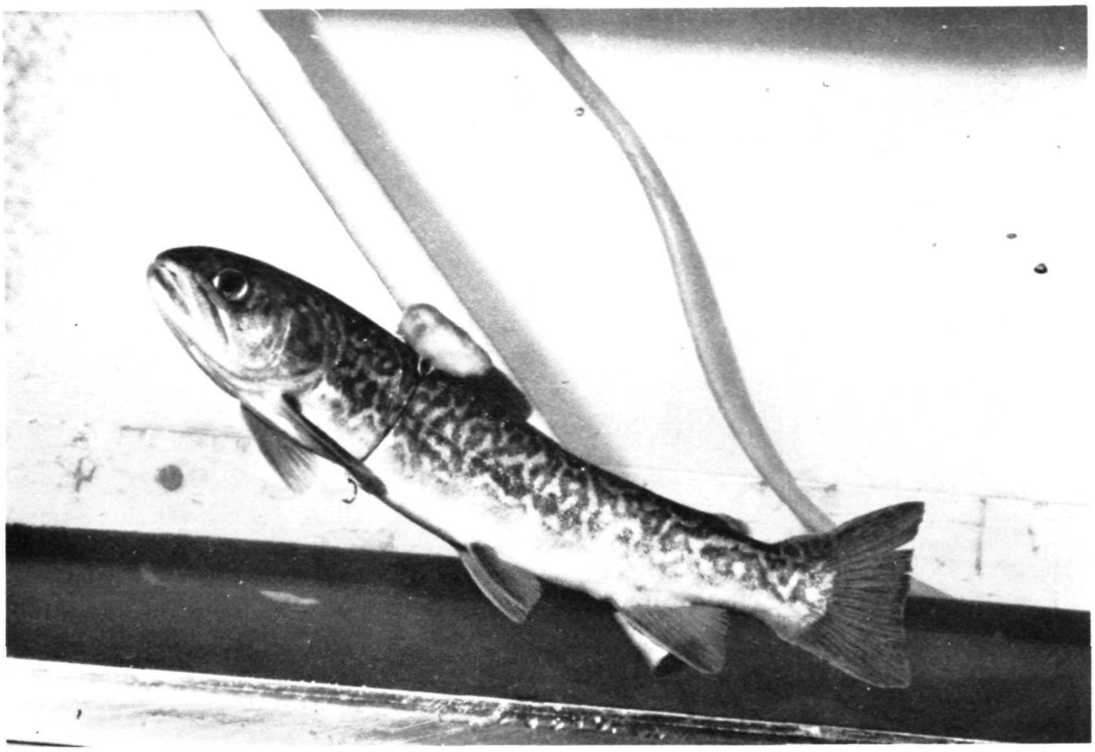

Fig. 7. A trout carrying a neutrally buoyant radio transmitter on his back for recording electrical activity near the heart.

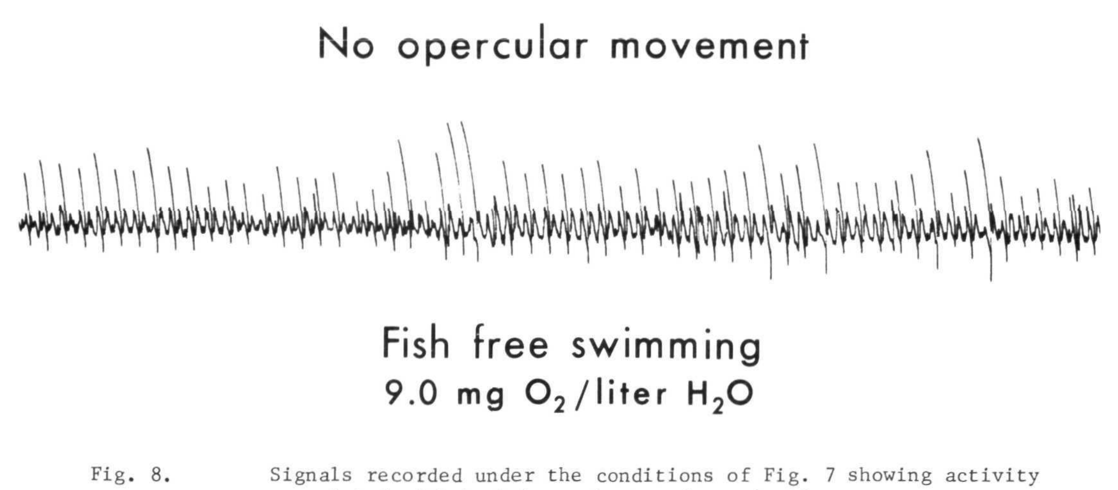

Fig. 8. Signals recorded under the conditions of Fig. 7 showing activity associated with both heart beat and respiration.

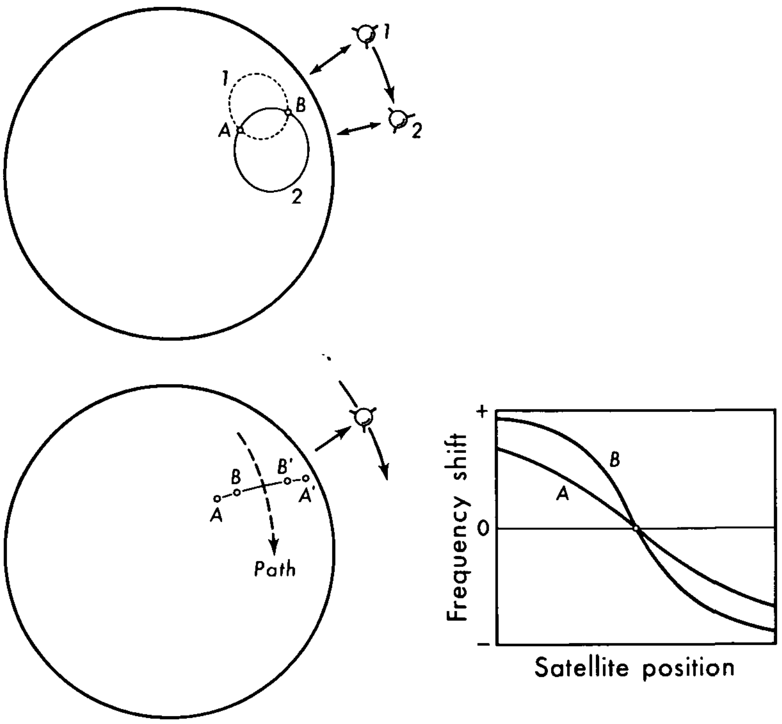

Fig. 9. Two methods for determining the position of a subject by an artificial earth satellite. At the top a transponder allows a series of range measurements in a wideband system requiring continuous activation of a receiver on the subject whenever the satellite might be near. Below is the Doppler system in which a transmitter alone is placed on the subject. From the slope and inflection point of the recorded frequency curve, the position of the subject can be determined, again with a resolvable ambiguity as to which side of the satellite track the subject is on.

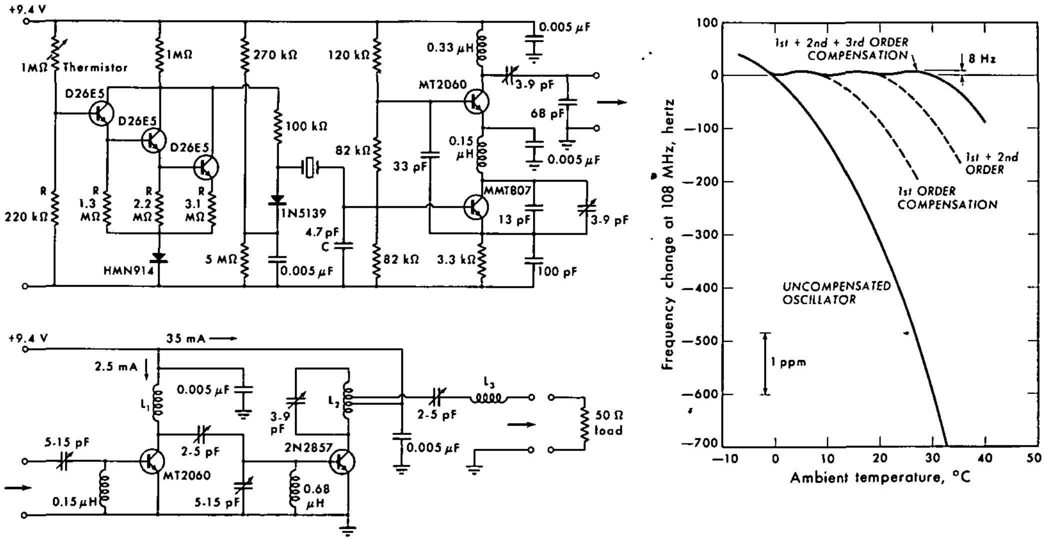

Fig. 10. Top: A relatively stable low power oscillator, with output stage, operating in the 100 MHz region. Resistors labelled R are readily experimentally adjusted to compensate any given circuit.

Right: Degree of temperature stability possible in the circuit tested. Not shown is approximately 20 Hz hysteresis for a temperature change of 20°C since such drift has little effect on the present application.

Bottom: Output stage containing a frequency doubler to provide greater power at 200 MHz. Construction is on a copper sheet.

L_1 is 6 turns #20 wire, 3/16" I.D.

L_2 is 5 turns #20 wire, 3/16" I.D.

Power supply tap 2 turns from collector.
Output tap 3 turns from collector.

L_3 is 8 turns #22 gauge wire, 3/16" I.D.

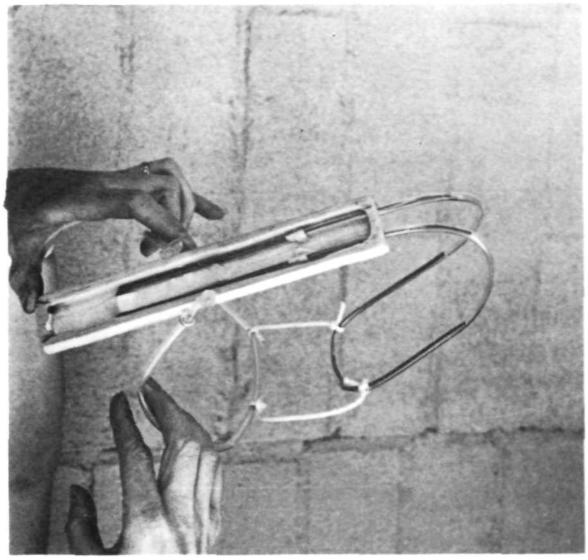

Fig. 11. Bird harness for extended experiments with rigid elements appearing dark inside the flexible plastic tubing.

Fig. 12. One alternative placement of the harness on a blackfoot albatross, before there has been time to preen it down into the feathers.

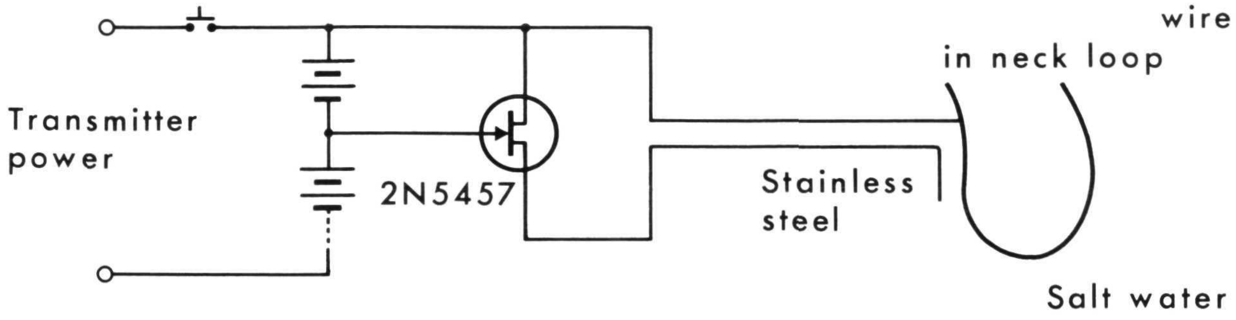

Fig. 13.

Release mechanism in which eventual depletion of the main power batteries connects the two dissimilar metals to cause corrosion in a supporting member.