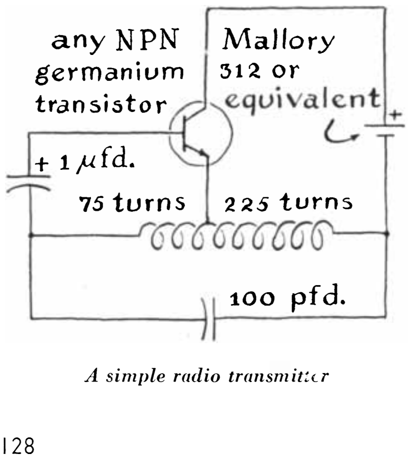
THE AMATEUR SCIENTIST

Little radio transmitters for short-range telemetry

Conducted by C. L. Stong

An amateur who builds a radio transmitter is likely to measure his success and pleasure in terms of the transmission range he achieves. In such terms there is more pleasure in talking with another "ham" across the country than with one in the next county, even if the more distant operator turns out to be a rather dull fellow. The aim of reaching out ever farther has spurred amateur radio operators to extend the range of their apparatus steadily; it was about five miles in 1900, rose to 5,000 miles by 1920 and reached 12,000 miles in 1930. The ultimate in distance was approached recently when an amateur in Finland communicated with one in California by means of signals bounced off the moon. The round trip was some 500,000 miles.

What next? R. Stuart Mackay, a physicist and biologist at Boston University, suggests that radio experimenters shift their enthusiasm to short-range telemetry. Here apparatus the size of a vitamin capsule radiates signals over distances measured in feet or even inches. The challenge lies in making the most of the least.



A simple radio transmitter

Most miniature transmitters carry devices for sensing one or more variables that may include temperature, pressure, displacement, vibration, acceleration, acidity or alkalinity, bioelectric potential, fluid flow, radioactivity, light, color and so on. Miniature transmitters, equipped with appropriate sensors, have been shot into the tops of trees, dropped into deep water, swallowed by various animals, enclosed in vacuum systems, ovens, reaction vessels and the rotors of centrifuges, cemented to the backs of turtles and tied around the necks of grizzly bears. Variations in the design and use of the little transmitters appear to be limited only by the imagination of experimenters.

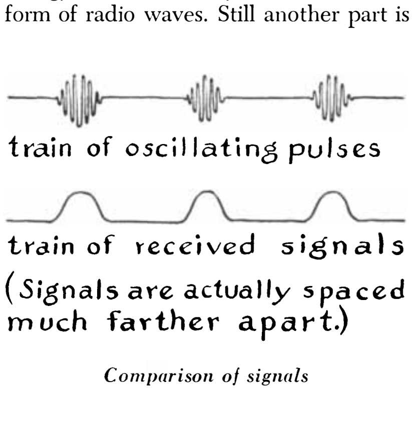
Short-range radio telemetry is fairly new. When I asked Mackay for the best way to get started, he lent me the manuscript of his forthcoming book: *Bio-Medical Telemetry* (John Wiley & Sons, 1968). The following discussion is based on that information and on my own subsequent experiments. I learned that one needs little experience in electronics to build successful transmitters but that the difficulty of construction varies inversely with the size of the units. When you attempt to make pea-sized transmitters, you develop admiration for the kind of craftsman who makes and repairs watches.

The electrical circuits and basic parts of the small transmitters are like those in conventional equipment in all respects except size. The equipment includes resistors, capacitors, transistors, dry cells, quartz crystals, coils of copper wire and so forth. All parts except the coils can be bought in miniature sizes. The coils must be wound by the experimenter. Extensive use is made of plastics for forms on which the coils are wound and for enclosing the apparatus. Transmitters that are to be immersed in fluids or swallowed by animals are first coated with wax and then covered with silicone rubber. The units are energized by mercury cells of the kind used in small hearing aids and electric wristwatches.

I chose the simplest transmitter for my first experiment. The device is easy to make, has interesting applications and usually works on the first try. The circuit is known to electronic engineers as a Hartley oscillator [*see illustration at bottom left on this page*]. The coil that is illustrated in the lower part of the drawing and the capacitor shown at the bottom form a resonant circuit in which electrical oscillations occur at a characteristic frequency. A charge of electrons, when placed on one side of the capacitor, tends to distribute itself equally on both sides by moving through the coil from the charged to the uncharged side. The flow creates a magnetic field around the coil.

It would seem reasonable to suppose that the flow would stop after the charge became equally divided. The magnetic field is now present, however, and it must collapse. In collapsing the field cuts through the turns of the coil and generates an electric force that keeps the electrons moving toward the formerly uncharged side. The situation soon becomes as unbalanced as it was in the first place, so that the action reverses. The electrons rush back to their initial position and then are ready for the next cycle.

Were it not for the loss of some energy during each transit, the electrons would slosh back and forth endlessly. However, some of the energy is spent during each transit in heating the coil and the capacitor. Another portion of energy is radiated by the coil in the form of radio waves. Still another part is



Comparison of signals

lost when the undulating magnetic field that surrounds the coil generates alternating currents in nearby conductors.

It is this last part of the energy that most interests those who experiment with short-range telemetry, because the energy is strong enough to actuate a nearby radio receiver. The oscillations gradually die away, much as a playground swing eventually comes to rest. A swing vibrates at a characteristic frequency that depends on the length of the swing and the strength of the force of gravitation. Similarly, electrical oscillations in a resonant circuit vibrate at a frequency that is determined by the size of the coil and the capacitor.

Swings can be kept going by a series of periodic pushes. Electrical oscillations can likewise be kept going in a resonant circuit by adding charge to the capacitor each time the current sloshes back and forth. Periodic charge can be added by connecting the capacitor momentarily to a dry cell with a fast-acting, automatic switch. A transistor can function as a switch of this kind.

The dry cell is connected to the capacitor through two electrodes of the transistor—the emitter and the collector. Normally the path between these electrodes resembles an open circuit. If a weak current is made to flow in one direction through the emitter and the third electrode of the transistor, called the base electrode, the switch is "on," but when the voltage reverses, the switch turns "off." The dry cell is then connected to the capacitor for a moment until the current again reverses and turns the battery off. In the transmitter under discussion the alternating current that activates the transistor is taken from part of the coil (through a tap that is connected to the emitter) and is fed into the base of the transistor through a one-microfarad capacitor.

This circuit is designed to oscillate for a brief interval, turn off for a much longer interval, oscillate again and so on. The pulsing action arises from another characteristic of the transistor, which is that the transistor contains an internal junction between the base and the emitter; the junction acts as a one-way valve for electric current. Current can pass from the base to the emitter, but it encounters resistance in the opposite direction.

Because of this rectifying action, charge gradually accumulates in the one-microfarad capacitor. After some hundreds of oscillations the charge becomes so large that it suppresses the switching action. Oscillation then stops while the accumulated charge slowly leaks through the transistor.

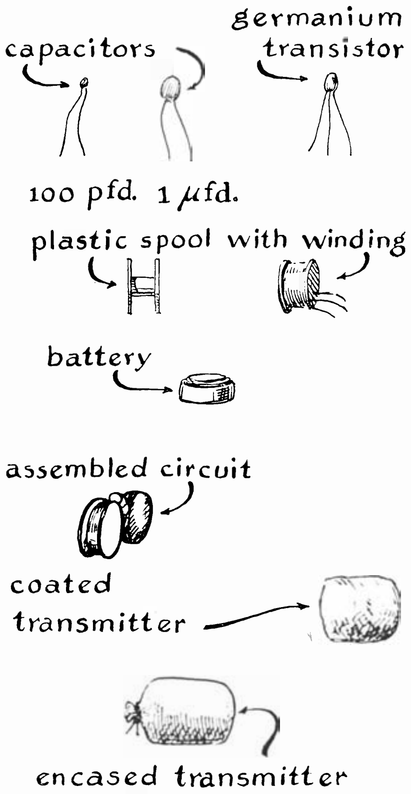
Some transistors are leakier than others. Those made of germanium leak at a rate that varies with the temperature of the device. Indeed, germanium transistors are so responsive to changes in temperature that they make excellent thermometers. The circuit under discussion includes a thermometer of this kind. It has been used for telemetering the internal temperature of things as diverse as the rotor of a centrifuge, a batch of setting concrete and the gastrointestinal tracts of animals.

The signals can be picked up by an ordinary transistor radio placed within a few feet of the coil of the transmitter, where the pulsating magnetic field carries the information. Each burst of oscillations is heard as a distinct click. The frequency of the clicks increases with the leakage of the transistor, and the leakage increases with temperature. The unit can be calibrated in terms of temperature by placing the transmitter and a thermometer in a beaker of cold water and making a two-column table that lists the frequency of the clicks and the corresponding temperature as the water is warmed. A calibration graph is then drawn by plotting click rate against temperature.

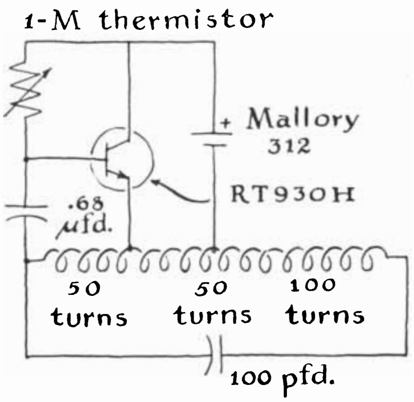
The clicks can be timed with a stopwatch. When a count is being made, accuracy will be improved if the observer swings his arm up and down in unison with the clicks. This trick enables him to continue the count if he is momentarily distracted by a burst of incidental noise. Always assign "zero" to the first click and simultaneously start the watch: count "zero," "one," "two" and so forth.

My first transmitter was about the size of a pack of cigarettes. Smaller versions were made later. Any germanium transistor of the NPN type will work in the circuit illustrated at bottom left on the opposite page. Any germanium transistor of the PNP type can also be made to work by reversing the connections to the dry cell. The coil can be made of insulated copper wire of any size and should be slop-wound. I just wrapped it around a pencil. Do not wind the coil as a neat, single layer.

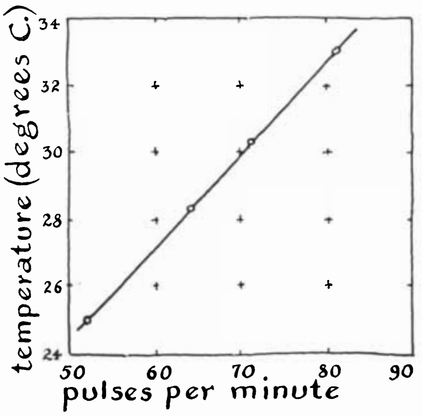
The tap to which the emitter connects can be brought out of the coil as a short loop. The completed coil can be coated with epoxy and should be slipped from the form on which it was wound. I wound several coils on tiny spools, but it was a needless waste of time. When soldering transistors into a circuit, clamp the leads between the jaws of a pair of



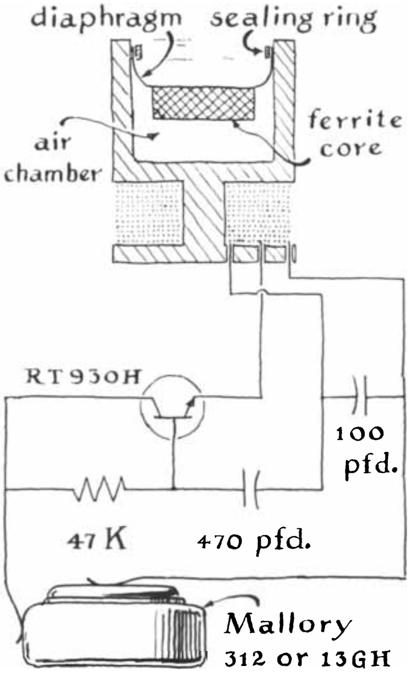
Elements of transmitter



Temperature-sensing transmitter



Transmitter calibration graph



Pressure-sensing transmitter

long-nosed pliers at a point between the device and the hot joint. The jaws act as a heat sink and keep the transistor cool.

Soldered connections can be insulated with a dab of quick-drying cement. The physical layout of the parts is not critical. Transmitters of the smallest size are made by sandwiching the capacitors and the transistor between the coil and the dry cell [*see top illustration on preceding page*].

Coils of the smallest size are wound on a Teflon form. One end of a Teflon rod, approximately 1/4 inch in diameter, is machined into a cone that is about 1/4 inch long and 1/16 inch in diameter at the base and tapers toward the end about one degree. The conical projection should be polished. A perforated disk cut from the same stock slips onto the tapered projection and should make a tight fit at a point about 3/32 inch from the shoulder of the rod. The coil is wound in the space between the inner face of the disk and the shoulder. Epoxy cement is applied as the wire is wound. The coil is slipped off the form when the epoxy has hardened. (Epoxy does not stick to Teflon.)

When winding coils of 40-gauge wire (.003 inch in diameter) or less, uncoil the wire from the end of the spool. Attempts to pull off the wire by rotating the spool invite a break. When this happens, it is almost impossible to locate the broken end. Insulated wire of 40 gauge and other components for the transmitter can be bought from Allied Radio, 100 North Western Avenue, Chicago, Ill. 60612.

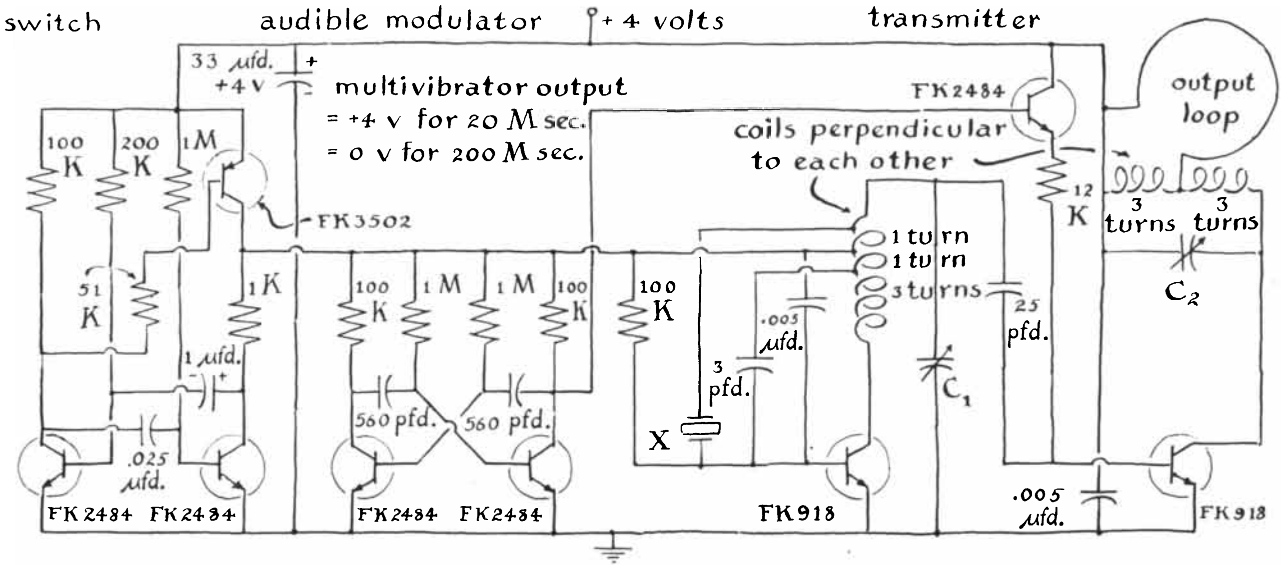
Connections can be spot-welded directly to mercury cells (see "The Amateur Scientist"; SCIENTIFIC AMERICAN, November, 1966). A miniature soldering iron for making minute splices can be improvised by brazing a short length of 12-gauge copper wire to the replaceable tip of an ordinary electric soldering iron. A hot knife, useful for opening epoxy housings, can be similarly improvised by brazing the blade from a pocketknife to a replaceable soldering tip. Fully assembled transmitters are first embedded in epoxy and then coated with wax. If they are to be swallowed, they should also be enclosed in the tip cut from the finger of a rubber glove and tied with nylon thread, as illustrated.

The performance of the transmitter can be altered in a number of ways. For example, the frequency of oscillation can be increased by substituting a smaller capacitor for the 100-picofarad unit specified. (A picofarad is a millionth of a microfarad.) The frequency can also be increased by winding a coil of fewer turns. (The position of the tap should be shifted in proportion toward the near end of the coil.)

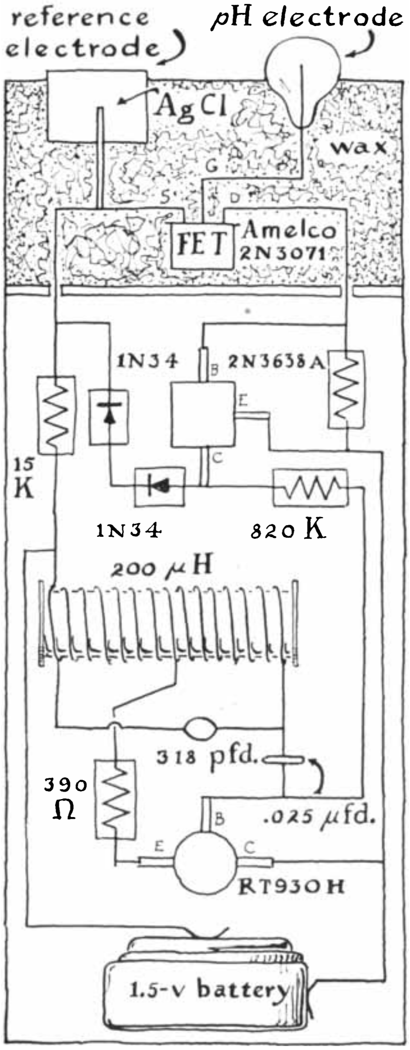
The frequency of the clicks can be increased or decreased by using a smaller or larger capacitor in the position of the specified one-microfarad capacitor. The shape of the magnetic waves emitted by the oscillator can be altered either by shifting the position of the tap on the coil or by inserting a variable resistor of approximately 600 ohms in series with the lead that connects to the emitter. The strength of the emitted signal can be increased by applying a higher battery voltage to the unit.

The time required for the transmitter to respond to changes in temperature can be reduced by adding a separate thermistor to the circuit. The thermistor must be added if a silicon transistor is used [*see middle illustration on preceding page*]. In the transmitter shown the battery was connected to the center of the coil to increase the strength of the signal.

For the quickest response to changes in temperature the thermistor is mount-



Circuitry of R. Stuart Mackay's long-range tracking transmitter



Transmitter for sensing pH

ed either on the surface of the transmitter or externally as a separate unit. The transmitter can be made responsive to changes in pressure by suspending close to one end of the coil a piece of magnetic material, such as a thin disk of ferrite. The disk is supported by a flexible diaphragm [*see top illustration on page 130*].

The disk can be sawed from the end of a cylindrical "loop stick." Such sticks are available from dealers in radio supplies. The diaphragm can be cut from any thin sheet of plastic (such as Saran Wrap) that is relatively impermeable and assembled in the cavity of a coil form machined from a plastic rod.

Increases in the pressure of a fluid in which the transmitter is immersed move the ferrite disk toward the coil, thus increasing the inductance of the coil and lowering the frequency of the radiated signal. The inward motion of the diaphragm also compresses the trapped air, creating a restoring force that moves the ferrite away from the coil when the external pressure falls. Changes in pressure are sensed by the receiver as changes in frequency of the radiated signal. The tuning dial of the receiver can be calibrated accordingly. The transmitter, when so constructed, can be used simultaneously for telemetering both temperature and pressure.

Although almost any radio receiver will pick up the signals, some receivers work better than others. The best ones must be found by trial. Take a transmitter into a radio store and try it on an assortment of receivers. Select for additional test those receivers that tune most sharply and appear to be most sensitive.

Take these receivers outside the building. In large cities some of the receivers will pick up several interfering broadcasting stations at the same time. Buy the one that is most selective. Usually little correlation is found between size, price and quality. Many experiments can be conducted in which the receiver is within two or three feet of the transmitter. In such experiments signals of adequate strength are picked up by the antenna built into the receiver. Depending on the physical arrangement of the experiment, however, it may be desirable to equip the receiver with a loop antenna consisting of one or more turns of wire connected to the input terminals of the set. When one is making studies of caged animals, for example, a loop antenna can be installed inside the cage, or below it if the bottom of the cage is made of insulating material.

Occasionally the experimenter may be interested only in the location of a free-ranging animal—for example such burrowing animals as gophers and moles. Here wires can be stretched over the ground in an even pattern that will ensure a wire's being near the animal at all times, so that a clear signal is consistently obtained. (It is not difficult to improvise a small, comfortable harness for attaching the transmitter to a captured animal that is then released.)

To pinpoint the position of a transmitter within a given area the experimenter can stretch insulated wires in the form of slender, hairpin loops that form a pattern of crossed grids over the area. The loops should be about two feet wide; they can be hundreds of feet long. A transmitter that is within a foot or so of the intersection of two loops will generate a clear signal in each one. The observer pinpoints the location of the transmitter by connecting the receiver to each of the loops in sequence. The connections can be made by hand or, preferably, with an automatic switching mechanism.

Large animals that range over many square miles are tracked by transmitters more powerful than those that send out conventional radio signals. The frequency of these transmitters should be controlled by quartz crystals. The accompanying illustration [*bottom of page 130*] shows the circuit of a transmitter that has an effective range of several miles. The quartz crystal, which is designated *X* in the illustration, determines the frequency of the radiation.

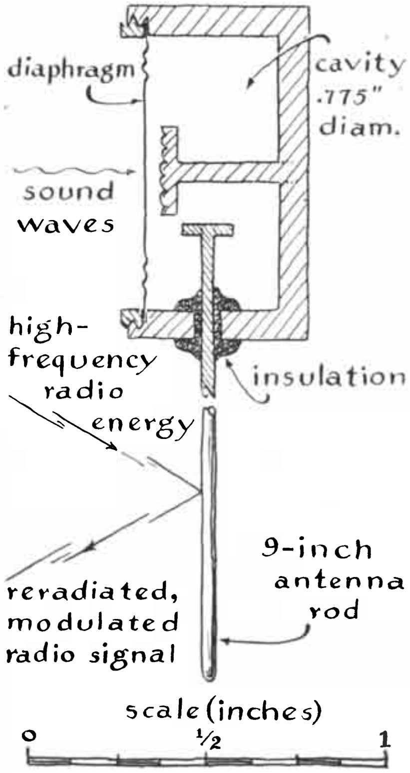
Highly directional antennas that resemble television receiving antennas can be used to follow an animal that carries a transmitter of this type. Two such antennas, spaced a known distance apart, are turned to the direction from which the signal is loudest. The position of the animal with respect to the observer is then calculated by triangulation.

A number of legal considerations must be observed by experimenters who operate radio transmitters of any kind or size. The regulations are altered from time to time, so that it is not possible to summarize them here. Information about them can be obtained from Ben F. Waple, Secretary, Federal Communications Commission, Washington, D.C. 20554.

Sensors of many kinds can be built into transmitters. Their variety is suggested by two examples. One unit, which can be made small enough to pass through the gastrointestinal tract of some large animals, measures and transmits *p*H—the relative acidity or alkalinity of surrounding fluids.

The active sensing elements of the device include a small but otherwise conventional glass electrode and a silver chloride reference electrode. Potentials developed across the electrodes are amplified by an electrometer circuit that employs a field-effect transistor. The output of the electrometer modulates the transmitter. This device is somewhat complex and not easy to construct.

At the opposite extreme is a transmitter that senses sound. Requiring no battery, it is powered by an external transmitter. Radio energy picked up by the antenna enters a small metallic cavity that is tuned, much like an organ pipe, to resonate at the frequency of a selected beam of radio waves. Sound waves that impinge on the thin metallic



A passive transmitter

diaphragm closing the cavity cause the diaphragm to vibrate and thus alter the natural resonant frequency of the cavity. This change, in turn, alters the strength of the signal that is reradiated by the antenna.

Devices of this kind that need no local source of energy are known as passive transmitters. Sounds that are within the transmission range of the reradiated signal can be heard in a radio receiver. A minute transmitter of this type, with an impressive transmission range, made international news in 1960 when Ambassador Henry Cabot Lodge reported to the United Nations its discovery in a wall hanging of a U.S. embassy.

My experiments have been made mostly with transmitters of the Hartley type. I have had only one brush with failure, but even this experiment turned out well. With the cooperation of a local veterinarian, I fed a temperature-sensing transmitter to my dog. The animal emitted gratifying clicks for two days, and I started to draw a graph of variations in temperature along his gastrointestinal tract. On the third day the transmissions mysteriously ceased. I immediately assumed that the transmitter had failed. Later, however, I went around my yard carrying my receiver. In a far corner of the front lawn the signals came in loud and clear!