NASA Technical Memorandum 78590

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(NASA-TM-78590) A LONG-RANGE AND LONG-LIFE TELEMETRY DATA-ACQUISITION SYSTEM FOR HEART RATE AND MULTIPLE BODY TEMPERATURES FROM FREE-RANGING ANIMALS (NASA) 74 p HC A04/MF A01 CSCL 06B G3/51
N79-26762
Unclas
23482

May 1979

National Aeronautics and
Space Administration

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# A LONG-RANGE AND LONG-LIFE TELEMETRY DATA-ACQUISITION SYSTEM FOR HEART RATE AND MULTIPLE BODY TEMPERATURES FROM FREE-RANGING ANIMALS

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## SUMMARY

A long-range and long-life telemetry system for heart rate and multiple body temperatures from free-ranging animals has been designed. This system includes an implantable transmitter, external receiver-retransmitter collar, and a microprocessor-controlled demodulator. The size of the implant is suitable for animals with body weights of a few kilograms or more; further size reduction of the implant is possible. The ECG is sensed by electrodes designed for internal telemetry and to reduce movement artifacts. The R-wave characteristics are then specifically selected to trigger a short radio frequency (RF) pulse. Temperatures are sensed at desired locations by thermistors and then, based on a heartbeat counter, transmitted intermittently via pulse interval modulation. This modulation scheme includes first and last calibration intervals for a reference by ratios with the temperature intervals to achieve good accuracy even over long periods. Pulse duration and pulse sequencing are used to discriminate between heart rate and temperature pulses as well as RF interference. The implanted transmitter might be used alone for experiments on animals that frequent particular locations within a large territory; on animals in virtually any laboratory situation; or on animals in moderate-sized enclosures, such as those in a zoological garden. The implanted transmitter is otherwise interfaced with the receiver-retransmitter collar that employs commercial tracking equipment to achieve the long-range transmission. Peak energy is consumed only during the short RF pulses so that average current drain of either transmitter is in the range of tenths of milliamperes. The RF pulses from either transmitter are processed by the microprocessor controlled demodulator for the characteristics of pulse durations, intervals, and sequence. The output provides analog beat-to-beat heart rate and periodically updated temperatures as well as digital display. Heart rates to several hundred beats per minute (BPM) and body temperatures within a range of zero to 50° C with 0.1° C in resolution of change or better seem feasible. The objective of the design was to achieve a high degree of experimental flexibility and overall high quality in performance. The system was tested in prototype form on a dog.

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# INTRODUCTION

This report presents the design details and rationale of an experimentally versatile, long-range, long-life, telemetry data-acquisition system for heart rate and multiple body temperatures. The design comprises an implantable transmitter for short to medium range, a receiver/retransmitter collar to be worn by the animal for long-range transmission, and a microprocessor-controlled demodulator with a signal conditioner interface circuit. The other receivers and equipment that were used, including the collar transmitter, were obtained commercially.

The parameters of heart rate and temperatures were selected for this design for two major reasons. First, they have a low data rate requirement so that signal modulation is compatible with the same principles of operation of the small, long-range, long-life, telemetry tracking systems. Specifically, the radio frequency (RF) pulses can be infrequent and several milliseconds long as well as frequency-stable. These pulse characteristics allow narrow-band reception and pulse width discrimination in order to achieve the effective long transmission range at low power costs. Tracking systems have long been available and widely used (refs. 1,2).

Second, these parameters are substantially influenced, either directly or indirectly, by both the autonomic and central nervous systems, by the endocrine system, and by metabolism. Heart rate and temperatures, particularly in combinations, can therefore inherently serve to index many and various interactive responses of animals to their environments. These responses would include changes in activity, emotions, health, energy allocations, behavioral patterns, and biological rhythms. Illustrative examples have been presented elsewhere (e.g., refs. 3-5).

These parameters also require animal instrumentation techniques that are acceptable and not too difficult to use in a diversity of studies and environmental situations. That is, compared to the data of a tracking signal only, the gain of information from physiological data about the responses of an animal can far outweigh the added costs in the necessary initial procedural efforts of animal instrumentation.

Reviews and reference lists of the state of the art of physiological telemetry have been presented periodically (refs. 2,6-8). Pulse-interval modulation (PIM) in the telemetry designs for heart rate or temperatures is not uncommon (refs. 9-14). At least one design effort also has been able to obtain heart rates at long range with implanted and external relay transmitters (refs. 15,16). A temperature channel has recently been added to that system (Long, Department of Engineering, University of Wyoming, personal communication). Also, statements for the justification of studies that require physiological data from free-ranging animals and for the needs of associated research and development were prepared as a report from a NASA-sponsored 1973 Santa Cruz Summer Study and a subsequent Program Plan on Wildlife Monitoring (ref. 17). In short, the technical feasibility of a research approach and the justification for it have been demonstrated.

From the practical experimental point of view, however, the critical factor is the achievement of the quality of performance required to realize sampling procedures in experimental designs that are inherent in the idea of the use of indices. That is (except in the simpler applications), indices based on physiological parameters, such as heart rate and body temperatures, to assess animal responses will often require more or less continuous records over time in order to note relative changes. These changes can then be related to the experimental context and to the stimuli that give rise to the responses. Thus, large volumes of data are generated, and a high degree of automated data processing is virtually mandatory.

The system to be described here offers a heart rate and multiple body temperature capability but, in addition, has a number of features and advantages to improve signal quality and to increase experimental flexibility. The specific details of the circuits presented here represent a prototype that was designed, constructed, and tested in a Labrador dog at the Ames Research Center. A descriptive overview of the performance characteristics and design problems is presented first.

This work was initiated under the support umbrella of The National Research Council's Resident Research Associate Program and was continued, in part, through a grant (NSG 2293).

## OVERVIEW

The implantable transmitter generates a radio frequency (RF) pulse of several milliseconds duration for each heartbeat. These pulses are triggered from the specifically selected biopotential R-wave characteristics of the electrocardiogram (ECG). Tests with the prototype show that the R-wave detection is highly reliable. A crystal controlled oscillator is used to achieve the narrow-band, high-power density, and frequency-stable RF pulses.

Periodically, the transmitter's operation changes as determined by a heartbeat counter. This is set to be every 50 heartbeats in the prototype. A series of PIM temperature RF pulses are then transmitted within an approximate 1-2-sec window. This temperature pulse series is at the same RF as that for the heartbeats, but the pulse durations are approximately doubled. The modulation scheme includes a two-point interval calibration that helps to achieve continued accuracy over time with good measurement resolution over a wide temperature range.

These RF signal characteristics are then received either directly at short to medium range or after relay through the collar for long range. In either case, the received signals are appropriately conditioned by an interface circuitry and then processed by the microprocessor. The interface circuitry is adapted to condition a tone-burst output, in order to make it compatible with commercial tracking receivers and field tape recorders that might be used for temporary data storage. The microprocessor then sorts the pulses according to their widths and to the programmed data treatment for the other signal characteristics to give digital or analog outputs.

Since temperature variations occur slowly, the periodic cycle for transmission of data avoids unnecessary redundancy and conserves power both for transmission and for circuit operation. Also, the rates of change in temperature data are often correlated with heart rates so that sampling redundancy inherently increases with heart rate. The R-waves are still detected and counted by the implanted transmitter so that no information on the number of heartbeats is lost during temperature transmission. Because the temperature window is short, only a little heartbeat-to-beat information is lost.

On the other hand, the transmission of each heartbeat does not involve unnecessary redundancy. That is, animals that weigh only a few kilograms spend most of their time resting or engaged in moderate activity; their heart rates are then slow and match approximately a convenient pulse rate for location and tracking. The transmitter's duty cycle is still low so that further power reduction through reduced transmission rates is not really necessary. Operation time from several months to more than a year can be achieved, even within a small animal. Also, many experiments will require combinations between average heart rates for periods of time and beat-to-beat changes at other times. Such decisions about these formats are better made when processing the data. In this regard, the temperature cycle can be flagged optionally to obtain averages.

Figure 1 illustrates the various ways to interface the equipment for experiment flexibility.

## Temperature Modulation

The modulation scheme for temperatures is illustrated in figure 2. The scheme involves ratios with the calibration values that are based on fixed resistors within the transmitter's circuitry. The fixed resistors determine the first and last intervals of the series of temperature pulses. The intermediate intervals of the series are assigned sequentially to the respective thermistors; there could be several thermistors if desired, but only two are used in the prototype design. The interval between the 50th heartbeat that triggers the series and the first temperature pulse is also determined by the same calibration resistor. After the last temperature pulse, a brief delay is insured before the next transmitted heart pulse is permitted so that pulse separation always occurs. The fixed-calibration resistors are selected to correspond to the highest and lowest resistances of the thermistors used and the range of temperatures anticipated in experiments. A measured temperature interval is therefore a percentage of the range defined by the calibration intervals and is then related to the known thermistor temperature curves.

The ability to define limits for acceptance in demodulation of the pulse durations, intervals, and sequence characteristics helps guard against error. In addition, however, it allows the absence of error to be recognized automatically. That is, the microprocessor will not update unless conditions are met, and this fact can be known in an automated way. This is important when a telemetry system is used near the limits of its capabilities. Under such conditions, the feature of doubling the temperature pulses also inherently yields a periodic stronger signal. This flag, at least, helps to maintain the record of average heart rates when the noise interference for good beat-to-beat information is too great.

Because the relationship between the fixed resistors and thermistors is proportional, changes in circuit characteristics and power levels over time minimally influence accuracy. Because all the information for the PIM is transmitted in a short period of time, the variation in detection of the leading edges of the pulses ("jitter") within the pulse series should be slight. The degree of jitter from one pulse series to the next is of little concern. For example, a temperature range of 50° C with 0.1° C measurement resolution seems feasible within an average time requirement of less than 0.5 sec per temperature channel. The average from sample redundancy should improve this resolution.

## R-Wave Detection

The quality of performance of this and similar heart-rate telemetry systems depends first on the reliability of the R-wave detection independent of the animal's activity. Body movements and the choice of electrode locations may cause variations of amplitudes, waveforms, and polarity of the ECG signals. There may be large and rapid changes in the regularity and frequency of heatbeats, and unwanted signals from various sources may cause false triggering. The idea of a chronic implant within a healthy and free-ranging animal must be kept in mind when trying to achieve an optimum degree of success to correct for these problems. The implant must be packaged adequately, and appropriate surgical procedures must be followed in addition to giving considerations to both sensor and circuit design. Simplicity and economy are desired for any solution, but not at the expense of experimental objectives and performance requirements. The optimum also will not be identical for different species or, for that matter, for different experiments with the same species. The direction taken here allows design and procedural variations to be made easily and noninteractively.

A reasonably good first approach when the transmitter is implanted is to locate the electrodes subcutaneously on the thoracic region. The R-wave amplitudes tend to be greater when one electrode is referenced to the other located near the apex of the heart and relative to the heart's electrical axis. Amplitudes within the ranges of several tenths of a millivolt to several millivolts will often be obtained, but this depends on the species as well as on electrode location.

The frequency spectrum for the ECG is 0.1 - 100 Hz. Empirical examination with the use of filters will indicate that dominant frequency components of R-waves occur at about 20 Hz. This is somewhat dependent on heart size and rates. Filtering above that frequency substantially reduces the electromyogram (EMG) in which the frequency components begin at about 30 to 50 Hz. The amplitudes of the EMG tend predominantly to be less than a few tenths of a millivolt unless a major muscle mass is involved. Skeletal muscle is anatomically unlike that which produces the behavior of an electrical syncytium in cardiac muscle. A strong electrical axis between highly coordinated polarized and depolarized regions over a long distance, as from the heart, does not occur. Location of electrodes away from muscle is therefore beneficial.

Low-frequency signals within a few hertz, such as those caused by respiratory movements, are filtered also. But amplitude changes in the signals of successive heartbeats can be substantial because of the influence of thoracic changes on the electrical axis. Changes in body position, which shift tissues and organs, also influence the electrical axis. Beat-to-beat changes in amplitudes in excess of 40% tend to be very rare and are usually much less if care is taken; however, amplitude changes over time are of course greater. It is important, therefore, to select electrode locations to reduce this variation as well as to maximize R-wave amplitude. Signal polarity changes are controlled by rectifying the signals. Automatically adjusting thresholds help to compensate for amplitude variations and to maximize noise discrimination whenever possible.

There is a variety of other signal detection problems. Excessively large potentials, which can occur, can overdrive the amplifier; discontinuous signals can cause ringing oscillation within circuits; and accentuated T-waves may occur with respect, in part, to electrode placement and cause double triggering. T-waves can usually be controlled to be less than 50% of the R-waves. P-waves tend to be much smaller but do precede the R-wave. Fortunately, the wave forms of the ECG tend to keep a degree of amplitude proportionality so that automatically adjusting thresholds have considerable benefit. Triggering from RF feedback within the circuit or through external leads requires appropriate preventive measures, such as filtering and packaging. Spikes from stress at lead connections can occur if proper care is not taken. Lead movements can induce potential differences at the transmitter's input when the leads are separated and when there is a high impedance. This problem is reduced when the transmitter is inside the animal's body but might be heightened by a strong RF field during signal outputs. Changes of the transmembrane potentials of cells due to pressures of electrodes, and as different from activation potentials, might occur also.

In practice, many of the unwanted noise artifacts occur in the form of spike bursts rather than single spikes. A few of the spikes in a burst will have higher amplitudes than most of the others. Although these spikes are often close together, their amplitudes may exceed a triggering threshold. Rapid retriggering might occur unless limited. Nevertheless, such limits must not exceed requirements for maximum heart rates. Maximum heart rates of animals that weigh more than 1 or 2 kg rarely exceed an upper limit of as much as 8/sec. This allows 125 msec as a minimum limit for retriggering and that limit could be extended if maximum rates are lower. This minimum limit for retriggering also helps to traverse the intervals of rectified waveform complexes and might be extended to overlap T-waves. Electrode movement artifacts can be a major problem because their signal amplitudes and frequency components range widely and overlap those of R-waves. Appropriate electrode design and implant procedures are critical here, and some suggestions will be made shortly.

In effect, the circuit design for the detection of R-waves places a window for signal characteristics among those anticipated after appropriate animal instrumentation procedures are followed. Sharp high- and low-pass filtering limits the frequency components above and below about 20 Hz. A limit on the accepted rate of change of slope of an incoming signal is also used. Amplifier gain control during RF pulses helps reduce feedback in addition to filtering. Full-wave rectification reduces polarity reversal problems and is combined with limits on retriggering rates. An absolute minimum amplitude threshold is set at about ±0.3 mV to keep above low-level signals and noise. Minimum R-wave amplitudes therefore must exceed this level. In addition, the triggering threshold automatically and proportionally adjusts itself above this minimum to accommodate beat-to-beat amplitude variations and anticipated durations of rectified waveform complexes, such as noise bursts. Precautions are taken to ensure rapid recovery in performance of the circuits, should unusual input signals occur

Again, the design is flexible so that adjustment in the specifications for performance requirements are largely noninteractive. The design is complex, but makes efficient use of available low-powered integrated circuits for construction. Also, the advantages that can be gained, if R-wave detection is accomplished reliably by the implanted transmitter, substantially overshadow the subsequent problems and limitations associated with complex waveform transmission of the ECG when only heart rate ultimately is required.

## Electrodes

Relatively small structures, such as wires, needles, and lead-loop extensions of stainless steel are often suggested for chronically implanted ECG electrodes (refs. 18-22). Stainless steel is a convenient metal to use and is tolerated reasonably well by tissue; an alternative metal like silve is less durable and somewhat toxic (ref. 23). The small mass is advocated to reduce inertia problems and, because the skin boundary encountered by external electrodes is absent, the impedance of an internal stainless steel electrode is relatively low even for small structures that have areas of only a few square millimeters (refs. 19,20,24). Secure suturing, the promotion of tissue imbedding, and an appropriate choice of locations where body movements are minimal are often indicated procedures to reduce movemen artifact problems. Neuman (ref. 22) recently illustrated that a multistranded lead-loop extension is a typical design commonly used for internal telemetry.

These electrode styles are not recommended here. A large distributed area, smooth, thin, and inflexible stainless steel disc is a better yet still simple design that is suitable for chronic subcutaneous implants in active animals. An example that is compared with a lead-loop extension is illustrated in figure 3. This particular construction involves a groove and plurality of holes into which the lead is fitted with support tabs and spot welded into place. Silicone RTV coats and supports the entire region of connection and binds to itself across the holes in the disc as well as to the disc. The RTV also is tapered to the lead to reduce flexture stress. The four holes near the periphery allow the disc to be firmly sutured in place so that lead movements do not dominate electrode movement, as is the case with a small mass electrode.

Figure 4 shows the considerable difference in signal quality that can occur between the disc and lead-loop extension electrodes that were illustrated in figure 3 and when in vivo. For these records, the electrodes had been implanted 1 week earlier in a dog; they were placed side by side subcutaneously in the lead II configuration across the sternum. The leads passed transcutaneously and were connected by clips to the recorder with one pair for recording while other test pairs served for ground. Filters were set at 1.0-100 Hz; the preamplifier input impedance was 200 kohms. The dog was kept walking in a circle with side steps of the forelegs. The records were made sequentially with disc electrodes in A, and then with lead loop extensions in B. Rubbing the skin directly over the electrodes produced an even greater difference in signal quality.

Figure 5 illustrates in vitro records from these two electrode styles when one member of a pair in a 0.9% saline bath was rubbed between the fingers in an attempt to simulate the in vivo condition. The records of the potential changes of disc electrodes (A&C) and lead loop extensions (B&D) are labelled respectively. The records A&B show the direct current potential changes; filters were set at 10-100 Hz for the records in C&D. A 10 Mohm input impedance probe was used. Polarity of the disturbed electrode is defined by the potentiometer connections. In A, the negative electrode was disturbed; in B, C, and D, the positive electrode was disturbed. Note that the artifacts are directed in sign opposite to that of the disturbed electrode. This as well as the severity of the artifacts depends on metal type; a steel electrode produced an opposite result. Electrode polarity orientation when implanted can therefore help differentiate between R-waves and movement artifacts. Large pieces of copper, silver, silver-silver chloride, and aluminum exhibited polarity changes similar to stainless steel. The half cell of stainless steel was positive to all of these metals; aluminum was most negative. Magnitudes of artifacts were least from silver and silver-silver chloride, but again, their use as for chronic implant is not recommended. A few of the more exotic electrode metals or materials might be preferred. However, comparative tests of electrodes should be based on an emphasis on resistance to perturbation as well as on rate of recovery, and on tissue response and physical shape that includes lead connections in order to relate theory to practice.

The records in figures 4 and 5 show that at least an order of magnitude of difference in the susceptibility to produce major spike-like disturbance artifacts can be noted under either of the in vivo or in vitro conditions. Even though the disc, by virtue of a larger area, should have a somewhat lower impedance, the impedance of the lead extension with a calculated peripheral area in excess of 10 $mm^2$ would not be expected to be high (ref. 24). But the induced variance in half cell potential is obviously high and occurs sharply for the lead extension when under nonstationary conditions. Even the use of a 10-Mohm input impedance probe in the in vitro tests was not adequate to counter this difference.

Aside from the structural suitability for an implant, some of the advantages of the disc seem to derive from the fact that the design widely and evenly distributes current flux and bridges large areas of tissue. Localized regions of either disturbance or cellular activity therefore would not dominate the entire electrode's behavior as would be the case with a small structure. On the other hand, large size would not diminish the ECG signal as expected if the biopotential were localized. Again, the ECG is generated throughout the body because the heart behaves as an electrical syncytium. Polarized and depolarized regions are created over a substantial structural distance. Even a large electrode cannot easily traverse that distance and thus tend to minimize its own net potential change relative to a distantly located reference electrode.

A plurality of electrodes or a flattened tube that is open at one end and insulated on the outside are alternative suggestions. A tube would increase the distance from surrounding tissue and tend to isolate the electrode interface from physical movements against tissue. A plurality of electrodes would further distribute current flux and may offer some advantage for minimizing amplitude fluctuations in R-waves as the heart's electrical axis changes. Maximum amplitudes, however, might be reduced because of the net potential difference across the separated parts of an individual electrode. These suggestions are secondary options, the implementation of which increases the procedural complexity; they may not be necessary. Also, flexible stainless steel mesh cloth of large area has been tried but was found unsuitable because of problems with lead connections and suture locations that seem to produce spikes. Also, the base potential difference produced by rubbing the mesh cloth when in vitro was substantially greater than that for the disc, but the spikes produced this way were about the same. A small disc has been routinely used for small animals and has been illustrated elsewhere (ref. 25). For example, good quality records can be obtained from rats running on a treadmill; a larger disc is better if animal size and skin thickness for revascularization after implant permits.

## RF Interference

Problems of RF noise interference and signal strength variations can, of course, cause difficulties with reception. At the implant to collar relay interface, a crystal-controlled, commercial, tracking transmitter was used. The transmitter was modified so as to be a complete slave to the output of the collar receiver and its associated logic circuitry. The logic circuitry delays the incoming pulse characteristics and then regenerates them for retransmission. Thus, the strong retransmitted RF cannot normally interfere with reception from the implant. The pulse width and intervals are maintained through the relay but the RF is changed to that of the retransmitter. The RF of both the implant and the collar transmitter are selected to be nonharmonic to reduce possible interaction. This separation is also convenient for experimental reasons. The use of different receiver bands is helpful in any new experiment to check coupling requirements between implant and collar. During experiments, the distance between the animal and the investigator's receiver will vary. When that distance is short, interference could occur if both transmitters had a similar frequency.

Because the implant produces a relatively strong RF signal, variations in signal strength are less troublesome when an attempt is made to achieve a good coupling with the collar receiver as the animal moves and changes body positions. Also, the collar receiver sensitivity can be minimal and less susceptible to extraneous RF interference. A wider receiver bandwidth is more feasible, and the power requirements are reduced in that a passive or only a slightly active gain need be employed. Thus, the size and weight of the external collar is not greatly increased over that required for the basic tracking condition.

The similar kinds of noise problems that occur at the output of the investigator's receiver are dealt with in the demodulation interface circuit in three basic ways. First, sharp band-pass filtering selects the tone burst generated by the incoming RF. Second, the RF sensitivity gain of the receiver is coupled to threshold detection; this involves a combination of manually set and autotracking modes to accommodate signal strength variations. Third, since much of the remaining extraneous RF noise involves short random pulses, pulse width discrimination of the received signals is used to block this noise and to sort the heart rate from the temperature pulses.

The tone bursts will not always be perfectly formed, particularly when near the limits of range; that is, the individual sine waves may be amplitude-modulated. A conversion to a square wave for pulse width discrimination is used and the top of the square wave is sustained for a brief period to stretch past a temporary attenuation. This period of pulse stretching must be short, however, so that only severe random noise could produce an output that is long enough to be accepted as a heartbeat.

## Packaging and Implant Procedures

Some comments and suggestions about packaging and surgical implantation procedures follow. The units should be hermetically sealed with appropriate headers, such as glass to metal, for lead passage out of the unit in order to prevent moisture penetration. The outer coat of the unit must be tissue compatible — silicone RTV can be used. Tissue, however, does not adhere to

RTV and a layer of Dacron coarse-weave cloth will facilitate tissue imbedding. This is strongly advised so that the unit can become firmly anchored within the body where it was originally sutured. When the implant is abdominal, some Dacron should be added to the leads where they will pass through the muscle wall to run subcutaneously. Appropriate sutures should be taken in that region to prevent slippage, to promote healing and reclosure of the abdominal cavity, and to prevent lead flexure at that point from pressing outward against the skin. Revascularization of the overlying skin might otherwise be inhibited.

Sensors located subcutaneously should be placed to the side of the skin incision to facilitate revascularization of the skin. All such objects should be sutured in place rather than left to float, in which case they may be more easily rejected or change location. The electrodes in particular must be well sutured for stability. An appropriate amount of lead slack is necessary so that sensors will not be stressed when the animal extends its body. Flexure stress at the lead/sensor junction is minimized also if the lead path into the sensor is not curved. Again, in no case should the leads or sensors exert an outward pressure against the overlying skin; even if healing occurs initially, a constant outward pressure to the skin may later cause rejection. A conservatively placed suture will usually alleviate problems of pressure from lead flexure and help to guide the lead path. Tight sutures around the leads or sharp angles, of course, cannot be tolerated. The job of channeling subcutaneously is not difficult, even in fairly large animals if appropriate tools are used (ref. 26).

A good flexible lead can be made with multistrand stainless steel wire, silicone tubing, and self-leveling silicone RTV. In some cases, it is adequate simply to insert the wire into a section of tubing and then inject the tube with the RTV. Greater flexibility can be achieved by coiling the wire within the tube. This can be done by coiling the wire around a piece of small-diameter metal tubing which is then inserted into the silicone tubing. The metal tube is then withdrawn. If necessary, the silicone tube can be temporarily expanded by soaking it in xylene; the xylene later evaporates and the silicone shrinks approximately to its original shape.

The common practice of using solder and solder flux to make connections to leads can cause problems. Tissue toxicity responses and the deterioration of the connection due to the battery potentials that arise from the metal discontinuities and due to the flux chemistry are likely. Spot welding, bolting, and crimping are better ways of making connections. Coating these connections, with RTV, for example, adds protection, reduces flexure stress, and offers an increased impedance boundary against electrochemical potentials.

The use of gas sterilization techniques, for example, with ethylene oxide, is recommended. The gas penetrates the outer potting materials. Zephiran chloride can then be used as a surface cleaning agent during implantation to reduce the possibility of contamination. Because heat and pressure are often used with gas sterilization, care should be taken to avoid damage to the potting materials or to the transmitter unit.

After the implant, closure of the skin might best be done with steel or a monofilament suture. Silk can act as a wick that might promote infection. It is best to use permanent sutures for the implant and for abdominal closure, however, rather than absorbable sutures. Antibiotics should be generously used, and their direct application to the implant and surgical area seems helpful in preventing initial infection problems. During surgery, skin separation from the underlying tissue should be kept to a minimum; the loss of vascularization promotes subsequent edema and results in cold regions that inhibit rapid healing. It is recommended that the animal's fur be shaved sparingly and that a temporary bandage be applied for support and warmth (the bandage should still allow exposure to the air). Talcum powder along with the topical antiseptic helps to keep the area dry. Of course, animal behavior after surgery and within the experimental situation influences procedures. An implant under field conditions should be done only after these things are known, particularly if the animal is to be released immediately without a day or two of confinement for purposes of observation.

## IMPLANTABLE TRANSMITTER CIRCUITRY

Figure 6 is a block diagram of the implantable transmitter; figure 7 shows the entire circuit design. The major functional stages are indicated by capital letters to correspond with waveform outputs of these stages as shown in figures 8 and 9.

The RF bypassed input voltages to the R-wave detector stage are first limited by a voltage follower whose "slew rate" is set at ±1 mV/msec (fig. 6)Ⓐ. This allows normal excursions of the QRS complex while greatly reducing the magnitude of large-amplitude, sharp signals which might drive the filter and amplifier circuitry into distortion (refs. 27,28). The next stage is a six-pole, low-pass filter (ref. 29). It provides a 36 dB per octave rolloff with a 3 dB point (70% amplitude) at 31 Hz Ⓑ. Its output is connected to a two-pole, high-pass filter with a 3 dB point at 18 Hz and a rolloff of 12 dB per octave Ⓒ. This filter circuitry provides a band-pass centered near 26 Hz with a sharp rolloff at higher frequencies and a lesser rolloff at lower frequencies. These filter characteristics select the fundamental frequency component of the R-wave while greatly attenuating other components. An AC coupled amplifier with a gain of 56 is next Ⓓ. Gain was set to accommodate ECG amplitudes within a range of ±5 mV. A precision full-wave rectifier converts the amplifier's output to an absolute value so that all signals are then positive regardless of the polarity of the input signal Ⓔ. Total gain is reduced to unity during RF transmission as a further precaution against spurious responses; this circuit is indicated later.

The remaining circuitry generates a constant-amplitude, 5-msec-wide pulse each time an R-wave occurs. It does this by identifying the highest peak in the rectified and filtered QRS complex by means of a peak pulse detector (ref. 30). The detector follows the amplitude envelope of the rectified QRS complex and stores the maximum level on a capacitor Ⓖ. As long as the input signal is positive-going and greater than the stored charge, this stage Ⓕ functions as a voltage follower. When the input waveform reaches a point of inflection and starts negative, the stored charge back-biases the diode decoupling the negative feedback loop. With the feedback loop decoupled, the stage functions as a comparator. Thus, the output swings into negative saturation since the inverting input is more positive than the noninverting input. If subsequent peaks do not exceed the stored charge, the output remains locked in negative saturation. Thereby, the last negative output transition occurs at the highest peak of a pulse complex.

The detector's output is connected to a biased CMOS line driver whose output Ⓗ controls a retriggerable monostable device. Unless retriggered, the monostable resets in 110 msec. But in the case where the peak detector is responding to a cluster of pulses with intervals less than 110 msec, the monostable may be retriggered several times, not resetting until 110 msec from the detection of the highest pulse. The reset Ⓙ drives a second, nonretriggerable monostable with a time constant of 5 msec. Thus, a 5-msec-wide pulse is generated Ⓚ for each detected R-wave. That pulse triggers the crystal-controlled RF oscillator Ⓢ via the combination of gate control circuitry (Q,R). The fixed delay of 110 msec does not affect the beat-to-beat measurement of heart rates less than 545 BPM. But this delay effectively is increased by a period selected in the gain control circuitry that leads back to the amplifier and rectifier (D,E). For example, the addition of 20 msec through that circuitry yields a rate limit of 461 BPM.

The 5-msec pulse Ⓚ also provides a reset control for the peak pulse detector. Reset is done by closing a normally open gate for 5 msec, discharging the capacitor on the detector Ⓖ. The level of charge left after the switch reopens is a function of RC values (G,I) and of the 5 msec. For example, a discharge voltage of half the previous peak amplitude allows the detector to track, on a beat-to-beat basis, changes in R-wave amplitude of 2 to 1. Thereby, the detector's threshold is automatically adjusted to provide a trigger level which is proportional by a desired amount to each measured R-wave amplitude. A resistive bridge in the discharge path of the detector sets the absolute minimum threshold level to ±0.3 mV and lower referred to the transmitter's ECG input. This ensures that the detector will not trigger on baseline noise when an adequate ECG is not present.

A restart circuit is provided in the event that the detector is driven into positive saturation such that the charge on the capacitor might remain higher than the subsequent incoming R-waves. In this condition, no triggering would occur to automatically adjust the threshold level. The restart circuit, which allows the capacitor to discharge until it reacquires the R-wave, activates 1 sec after the last detected heartbeat. The 1-sec delay is related arbitrarily to the expected lower heart rates. With a 1-sec value, the search mode would be employed at all beat-to-beat intervals of rates less than 60 BPM. For many animals, this may be a resting state when artifacts from EMG and electrode movements are least expected, except in such special physiological conditions as diving bradycardia.

The restart circuit itself consists of a resistor and capacitor connected across the battery supply. When the charge on this timing capacitor approaches $V_{dd}$, a gate connected to it closes. The detector's storage capacitor Ⓖ is now discharged through the gate via resistor to ground. The resistor determines the search rate as the threshold lowers to its absolute minimum. The RC combination Ⓛ that controls the gate provides the delay between the last heartbeat and the start of the search mode. Another gate is connected to the timing capacitor so that the search mode can be canceled. When closed, it discharges the timing capacitor to $V_{ss}$. This gate is closed each time the detector Ⓕ indicates a new pulse has been received. The search mode, therefore, is never employed at heart rates greater than the delay time, as seen in figure 8.

Besides keying the RF oscillator and adjusting the threshold on the peak detector, the 5-msec pulse generated by each heart beat initiates a counter divider chain and signal control to allow sampling of two temperatures periodically. The circuit diagram is included in figure 7. The significant waveforms are shown in figure 9. The R-wave pulse is divided by 50 using two CD 4017 decade counter dividers. A reset pulse (M) every 50 counts initializes the second CD 4017 and starts a third CD 4017 Ⓞ. The clock for the third counter (pin 14) is a multivibrator oscillator and has its period controlled by a resistance bridge. Four independent bridge circuits are provided, two with thermistors and two with the fixed resistors that provide a 0° C and a 50° C calibration. The four bridges are sampled sequentially by four CD 4066 switches controlled by the CD 4017 that advances one step following each pulse.

The oscillator operates as follows: A D30A3 is used as a constant current source to charge a 1-μF timing capacitor with the current-level variable proportioned to the voltage level derived from the resistance (thermistor) bridges Ⓣ. An NPN D26E1 emitter follower is used to compensate the emitter-base diode voltage of the D30A3. With the constant current from the D30A3 charging the 1-μF capacitor, a linear voltage ramp is generated starting at Vss. The ramp signal is connected to the negative terminal of the L161 comparator and the positive side is connected to the L161 output by a 2-to-1 attenuator. With the ramp signal below the positive terminal voltage, the L161 output is saturated at Vdd, and the 2-to-1 divider places a 0 voltage at the positive terminal. As soon as the ramp crosses this 0-V threshold the L161 comparator switches to an output of Vss and the positive terminal is also Vss. The L161 holds the Vss level until the 1-μF capacitor is discharged and then the entire cycle starts over again with the charge current from the D30A3. The ramp signal is operated between Vss and 0 since the L161 allows operation of the inputs all the way to the negative rail; but with a Vss to Vdd supply of 2.7 to 3.0 V, it will not work with a common mode voltage closer than 1 V to the Vdd rail. This ramp generator voltage range also provides the necessary collector voltage for the D30A3. The reset after each ramp period (proportional to the bridge voltage) is accomplished with a CD 4066 switch which is connected to the L161 output via a CD 4001 inverter. The return reset cycle is very short because of the low impedance in the switch. By adding a 3.3 kohm thermistor in series with the switch the reset period can be adjusted to 10 msec for the pulse width for transmitting temperature data Ⓝ. The enable circuit (P,Q) allows a time delay to capture the duration of the last temperature pulse and, in combination with the gain shutdown control (Q,D), ensures that a heartbeat 5-msec pulse will not overlap with that temperature pulse.

A number of considerations suggested that a thermistor bridge circuit would be more satisfactory than a direct resistor charging circuit for the timing RC. Since at least one of the thermistors and possibly both would be located remote from the electronic package, it was desirable and probably essential to use a low impedance thermistor. For instance, whether a 30-kohm or a 3-kohm thermistor is needed depends on the adequacy of moisture protection, and that is difficult to evaluate; therefore, the lower the thermistor value, the better the chance of maintaining consistent results. A 3-kohm thermistor at 25° C is about 10 kohms at 0° C (lower temperature extreme). For a 0.1° C temperature accuracy, a 0.04% resistance accuracy is required so that a shunt impedance of 2 Mohms across the thermistor would cause a 0.1° C error. A 20-Mohm shunt would give the same effect on a 30-kohm thermistor. This indicates that even with low-impedance thermistors, careful protection from moisture is essential.

If low-impedance thermistors (most desirable because of moisture problems) are used directly in RC timing circuits, two other problems occur. One is the switch impedance of the CD 4066 which is of the order of a few hundred ohms and deteriorates rapidly as the power source is reduced from 5 V to 3.0 V. This could represent a substantial impedance in series with the thermistor. Any significant variation in this impedance is likely to cause data errors. Because about 1 sec is allocated to retrieve the temperature data, very large capacitors would be required to obtain a suitable time constant with low impedance devices. Both of these problems can be circumvented by using a resistance bridge.

A D30A3 is used as a switch to power the four resistance bridges only when the approximate 1-sec temperature data are taken. The D30A3 is driven by a D26E1 so that the D30A3 can be properly saturated without loading the CD 4017 output. With the base current levels used, the voltage drop across the switch is typically 10 mV. Even this low voltage drop would cause readout errors if a bridge circuit were not used. Since all the bridge circuits (four each) are turned on with a common switch (D30A3), whatever voltage drop occurs in the switch is corrected for by the 0° C and 50° C calibration readings.

Minimizing the total power consumption is important to achieve an operational life of more than 1 year with a modest-sized battery. Although the CMOS devices are on continuously, they require very minute currents except during the short microsecond transitions between on and off states. The low-impedance thermistors would, however, represent a drain of many milliamperes if they were on all the time. Since the temperature is only sampled for 1 sec every 50 heartbeats, assuming an average heart rate of

100 BPM, this gives a duty cycle of 1 sec "on" and 30 sec "off." With typical thermistor values of 3 kohms and bridge resistors of 3 kohms, the "on" current for the four bridges is 2 mA; the average is 1/30 of 2 mA or about 60 μA. Switching each of the four bridges independently, which could further reduce the average current, did not seem advisable because extra parts would have been required and because of the possibility of error introduced by impedance variations in different switches.

Figure 10 shows a typical thermistor resistance vs temperature plot as well as various thermistor resistance bridge combinations. The tabled values were obtained with a breadboard bridge circuit and substitution of resistance to simulate thermistor impedances. Over the 0° to 50° C desired operating range, the thermistor changes about 10 to 1 in resistance and also is a nonlinear curve. Although a 3-kohm thermistor has been used for the data of figure 10, the shape of the curve would only change very slightly with a thermistor of a different impedance. The use of various bridge configurations results in a variety of possible curves. Limitations in the timing accuracy that can be transmitted within a limited RF bandwidth and using about a 1-sec interval for all temperature readings indicate that the raw thermistor 10-to-1 dynamic range is too large for proper use in this system. The approximately 3-to-1 range for the bridge curves seems about the best. A 1-kohm resistor is placed in series with the thermistor side of the bridge so that if the thermistor resistance were to short-circuit, the oscillator period would not be infinite. Such safeguards must be made in case a shorted or open thermistor lead causes the entire system to otherwise shut down. The bridge circuit plus some series resistance with the thermistors prevents such a failure and also yields identification intervals of such mishaps.

Some further manipulation of the bridge arrangement or resistance values could probably improve the dynamic range. This involves some sacrifice of the linearity but linearization can be done more easily through the demodulator. Calibration curves for the thermistor bridge in the transmitter circuit and with a 30 kohm thermistor are shown in figure 11.

As shown in figures 7 and 9, the temperature circuitry controls gating Ⓠ and Ⓡ to the RF oscillator's input Ⓢ and to the control circuitry to the amplifier gain Ⓓ. During a temperature measuring cycle, the 5-msec heart-rate pulses are replaced by the 10-msec temperature pulses, thereby doubling the oscillator's on-time. The R-wave counter nevertheless continues to advance so that the start of each temperature cycle represents the 50th heart beat exactly; only the dynamic beat-to-beat variation is interrupted temporarily.

The single stage RF oscillator is base-emitter tuned with a third-overtone crystal employed as the frequency determining device. The base-emitter circuit operates at the crystal's third harmonic of 54 MHz. The collector circuit is also tuned to 54 MHz. This configuration provides good frequency stability in a single-stage oscillator because the output load is effectively isolated from the base-emitter tuning loop. The oscillator's output is connected to the thermistor leads. These leads serve as the antenna, thereby optionally eliminating the need for a separate antenna. Bypassing RF is provided at the resistance bridge as well as at the ECG input and battery supply. The oscillator is keyed "on" and "off" by the ECG and temperature pulses so that it is active only during each pulse period. Turn-on time to full RF amplitude is within a few cycles of the 54-MHz operating frequency. Thus, the resulting wavefront slope is less than 20-μsec wide compared to the data pulse intervals of over 100 msec. Peak RF output power is about 8 MW.

The system uses two center-tapped mercury cells to provide ±1.4 V. Power consumption is the sum of the continuous current drain of the circuit plus the average peak current, which is heart-rate dependent. At a heart rate of 100 BPM, the average current drain is about 350 μA, of which approximately 250 μA is continuous.

Figure 12 shows the transmitter at various stages of prototype packaging for implantation and testing. The prototype unit was fabricated with discrete parts and integrated circuits. A further reduction in size would be possible using hybrid construction techniques, since the active components used are available in chip form. The battery shown has a 2400-mAhr capacity, thereby providing a maximum operating life of about 9 months at an average heart rate of 100 BPM.

The AM receiver used with this transmitter operates at 54 MHz, with an output frequency response from 0 to 10 KHz. The low-frequency capability is important since the received pulses can have durations as long as 10 msec. The amplitude is adjusted to provide the 0 to +5 V pulse heights necessary for driving the demodulator.

## RETRANSMITTER COLLAR CIRCUITRY

The retransmitter consists of an RF receiver, logic circuitry, and a commercially available animal tracking transmitter, all packaged within a collar. Figure 13 shows a prototype collar and field receiver equipment for a dog. Dimensions of the electronics package are 5 by 5 by 7 cm; weight is 320 g. Most of the size and weight is due to the tracking transmitter, which is 3 by 5 by 7 cm and weighs 277 g. The transmitting and receiving antennas are incorporated within the collar.

Figure 14 is a circuit diagram of the retransmitter; a circuit timing diagram is provided in figure 15 (the labeling with capital letters start over). At the input Ⓐ of the circuitry there is a passive RF receiver consisting of two tuning stages and a hot carrier diode detector. The stages are tuned for a bandwidth of about 8 MHz with a center frequency at 54 MHz. The receiving antenna is a flexible lead configured within the collar strap. Figure 16 shows the arrangement of the antenna lead. As can be seen, the lead begins and ends at the electronics package, with maximum extension to the collar's tip. The outgoing and return paths are separated for the width of the collar. Following the tuning stages, the hot carrier diode circuit detects the negative envelope of the incoming RF pulse Ⓑ. This detection provides an audio frequency pulse which is amplified Ⓒ and then reshaped by a comparator Ⓓ. Receiver sensitivity is adjusted by raising or lowering the comparator's threshold level. When practical, this adjustment is made with the collar on the animal. Otherwise, it is done prior to use by estimating the expected field strength and background noise for the particular application. Figure 17 shows an alternate receiver with a single stage of RF gain. This active receiver is used in the event that signal transmission from within the animal is exceedingly weak. This occurred during testing because of an antenna break. Variations in gain requirements can be expected for procedural reasons and size limitations among animals. The active receiver requires a greater current drain to operate, about 700 μA compared to less than 5 μA for the passive receiver. The antenna in either case is the same. The stage of RF gain in the active receiver causes a polarity reversal at the input to the comparator. This is easily remedied by interchanging the comparator's inputs.

The comparator drives the CMOS logic circuits which in turn generate a control pulse for actuating the RF tracking transmitter. The control pulses are delayed from the incoming receiver pulses, yet keep the same width and interval as received. The delay prevents interference of the strong retransmitted RF pulse with the reception of the weaker RF signal from the implanted transmitter.

To generate the delayed pulse train, the output of the comparator Ⓓ is connected in parallel to the inputs of a pair of monostable devices. One monostable triggers on the leading edge of the incoming pulse, the other on the trailing edge. Each provides a 20-msec-duration pulse which is complementary to the other. These outputs (E,F) operate a pair of gates Ⓖ that activates the transmitter Ⓗ when both are closed. As seen in figure 15, the delay and pulse width of the RF retransmission are the result of subtracting the outputs of the two monostables by means of the control gates. Receiver squelch during the RF retransmission is done by a blanking gate Ⓘ at the inputs to both monostable devices. This gate closes Ⓕ to Ⓘ before the retransmitted RF pulse and remains closed for about 100 msec. This insures that the retransmitter will not be self-triggered during that time and allows the receiver circuit a recovery time after each transmitted pulse. The blanking gate is controlled by a circuit which stretches the pulse output from the trailing-edge-triggered monostable. Because the collar was relatively insensitive to RF noise, it did not seem necessary to include circuitry to prevent the occurrence of a noise spike from triggering the monostable device. If that did occur however, the receiver would not accept another pulse for a period of about 120 msec; the occurrence of a heartbeat or temperature pulse could then actually be missed within that period. Initial pulse width discrimination in the logic circuitry could, however, be done with little added cost in terms of size or power requirements.

The tracking transmitter is a Telonic's Model MK-3A-TA-4 (fig. 13) with a factory-modified input. That is, the standard internal control of the RF pulse rate is omitted with control brought instead to a pair of external inputs. The companion receiver provided by Telonics is a hand-held model designed for field use. The receiver is crystal-controlled, as is the transmitter, and operates within the RF spectrum normally utilized in animal-tracking work. In this case, a frequency of 148 MHz is used. The output of the receiver is a tone burst applied to either a self-contained speaker or a headset. The duration of the nominal 2 kHz tone is determined by the width of the incoming RF pulse, in this instance either 5 or 10 msec. The tone burst is retained, rather than modifying the receiver to obtain a standard pulse, because it is readily recorded without distortion on a hand-held cassette tape recorder. Also, since the operator must adjust the receiver's output in the field without benefit of an oscilloscope, the tone is easily recognized using only the headset or speaker.

## RECEIVER DEMODULATOR INTERFACE CIRCUITRY

Once a field recording has been made, the magnetic tape is brought to the laboratory where it is replayed through a circuit that converts the tone bursts back to rectangular pulses compatible with the demodulator's input. Figure 18 is a diagram of the interface circuit. At the circuit's input is a band-pass filter (ref. 29). It is centered at 2 kHz, which is the receiver's output tone. A peak detector and a comparator then convert the sinusoidal waves within each tone burst into a group of rectangular pulses. The peak detector provides an adaptive threshold level for the comparator. Controls mounted on the front panel of the unit allow selection of automatic tracking rates and triggering amplitudes for the adaptive threshold. In addition, a fixed threshold level can be selected.

After the sinusoidal pulses have been changed into rectangular shapes, they are further filtered by means of a digital band-pass filter centered at 1.8 kHz. The filtered rectangular pulses are applied to a digital envelope detector which converts each group into a single pulse with a width of either 5 or 10 msec, as determined by the original transmission (ref. 31). The envelope detector can be adjusted to bridge across a single, missing pulse within a group. This allows the envelope to remain unchanged in the event that the comparator misses a single, sinusoidal pulse within a tone burst. This could result from an instantaneous amplitude fluctuation to which the adaptive threshold could not respond. These single pulse-to-pulse amplitude variations result from superimposed noise or quick changes in RF signal strength. Adjustment of the bridge duration is done by altering the time constant of $R_3C_3$.

Additional noise rejection is provided by a circuit which sorts out envelopes with less than 3-msec periods while passing those of greater periods, such as the 5 and 10-msec data pulses. Thus, single, spurious pulses within the 2 kHz band-pass are eliminated. Pulse rejection is determined by the time constant of $R_4C_4$.

The output of the interface circuit uses two voltage followers Ⓔ. One drives a lamp mounted on the front panel which indicates acquisition of data pulses. The other provides pulse height of the proper amplitude for driving the demodulator.

Front panel controls, besides allowing for selection of threshold functions, also allow the selection of frequency band passes in the event that the receiver has an output tone other than the nominal 2 kHz. This flexibility allows the recorded data to be retrieved according to the experimental conditions in the field or laboratory. As an example, data recorded in the field from a fast moving animal, with resulting RF signal strength fluctuations, would be handled differently from data recorded from a resting animal with nearly steady-state signal reception.

The interface circuit is low powered and can be operated either with batteries or a direct current power supply.

## DEMODULATOR CIRCUITRY

The microprocessor-based demodulator is used to accurately determine the time interval between pulses from the telemetry receiver output. It discriminates against unwanted noise and performs heart rate and temperature calculations based on the time-interval information.

To accomplish the accurate timing, a 2 MHz clock signal ($\phi 2$) used to generate basic timing operations inherent to the microprocessor is divided down to a 1 kHz signal (1-msec interval).

Figure 19 is a top view of the demodulator showing the internal component layout consisting of a central processing unit card (CPU), D/A output ports and converters; IK RAM/2K ROM card and a front panel/interval timer/interrupt generator, card. All microprocessor signals use the S100 bus system as a common element for communicating between the peripherals and the CPU card. The S100 bus provides, at a low cost, a variety of peripheral interfaces popular among the home computer hobbyists that are easily available at any local computer store (ref. 32).

A detailed description of the circuit operation of the demodulator follows.

The output of the telemetry receiver and interface circuit (fig. 20 pin J64) is buffered by IC 21 and fed to a positive and a negative edge triggered "D" type flip-flop (IC 5, pins 3 and 11). Their negative true outputs are connected to an eight-bit priority decoder (IC 6, pins 1 and 2).

The highest level of priority is pin 3 of IC 6. This input is reserved for a 1-msec timing interval generated by decade counters IC 2, 3, 4 and a divide by two flip-flop IC 1. The negative-going edge detector signal (IC 6, pin 1) has the next highest priority. The positive-going telemetered signal (IC 6, pin 2) is the lowest priority request.

When an input signal level change or a 1-msec interval occurs, the priority decoder generates an interrupt signal to the microprocessor (IC 6, pin 15). The interrupt signal causes the microprocessor to stop processing and to execute a vectored interrupt-service routine. A detailed description of the software routines is included in the appendix. Using the continuator to the service routine, the CPU (microprocessor central processing unit) reads either the time interval, R wave to R wave timing, or temperature cycle data. It then processes it and returns to the interrupted task.

The CPU acknowledges the interrupt request by sending an interrupt acknowledge signal, IRACK (ref. 33). The IRACK signal is used to clear the "D" type latch holding the interrupt request. It also allows the lower priority requests (if any) to be serviced in the same manner.

Figure 21 shows the view of the demodulator front panel for entering the command modes in the operation or calibration of the demodulator and displaying the real-time data. The switches are sensed by input port No. 7 to the 8080 card (fig. 22, IC 14, pin 8 and IC 15, pins 3 and 5).

The microprocessor reads the input instruction immediately after the power is "ON" or at any time the RESET key is depressed in the front panel. The RESET switch is connected to the CPU RST line and causes the displays to be initialized to zero, clears all memory, resets the time interval, clears all the interrupt latches and initializes the microprocessor program counter (internal to the CPU) to location zero. The calibration level (HI or LO) is read as an input when the software branches to the internal calibration routines.

Data to the front panel LED display is gated by the action of a demultiplexer (IC 13) and the output instruction status line IC 13, pin 6. The data, in BCD form, is latched to the LED displays by the six enable lines from the demultiplexer and held until a new reading is made.

The analog outputs are generated by three 12-bit D/A converters that require one's complement BCD data. The software complements the data and transfers the first 8 bits to two quad D type flip flops. All 12 bits are presented to the digital to analog converters when the software outputs the last 4 inverted bits to a quad D type flip flop and an 8212 is enabled, latching the 8 bits stored in the two 74LS175 latches.

The output of the converters are buffered and connected to the three analog output lines on the back of the demodulator.

## RESULTS AND DISCUSSION

The prototype of this system was tested on a dog. Preliminary tests were made with a transmitter breadboard mounted in a backpack worn by the animal. A standard ECG transmitter was also placed in the backpack. Two ECG electrodes were implanted subcutaneously with the leads brought out to the backpack where they were connected to both transmitters via an RF isolation junction. Chart paper recordings were then made while the dog was exercised within the range of the transmitters or on a treadmill. The recordings allowed the heartbeat pulses, derived from the new system, to be compared directly with the clearly identifiable ECG waveform. Results were positive with only an occasional heartbeat pulse being lost by the new system during periods of heavy exercise. ECG recorded during the same sequence of exercise showed R-wave amplitude fluctuations of ±35% on a beat-to-beat basis. The triggering threshold of the R-wave detector had been set for a tracking rate that would accommodate amplitude changes of less than this and seemed to account for the occasionally missing beat. A nominal tracking rate of 40 to 50% of R-wave peak should alleviate the problem. Signal artifacts occasionally occur also, but appeared to be due to movements of the external leads and connections rather than to the electrodes.

Next, the packaged transmitter was implanted in an 18-kg dog. Two ECG electrodes and one thermistor were attached subcutaneously. Another thermistor was located near the liver for measurement of deep body temperature. After 1 week, tests with the dog in a kennel were begun. The RF signal from the implanted transmitter was received, without retransmission, using a standard AM receiver. The output pulses were applied directly to the demodulator. The three analog outputs of the demodulator and the pulse train from the receiver's output were recorded on chart paper. This allowed the heart rate, on a beat-to-beat basis, and the two body temperatures to be correlated with the transmitted pulse train. Several recordings were made, the longest being 24 hr. The demodulator and receiver maintained lock during all recording sessions, as indicated by the analog outputs which followed the pulse train without dropout.

Tests of the retransmitter collar were made next with the dog still in the kennel. In this instance, the retransmitted pulses were compared to the directly transmitted pulses. This was done by recording the outputs from each system on a chart recorder. But this time the demodulator was driven by the RF transmission link. Again, the three analog outputs were recorded for correlation with the two pulse trains, representing the direct and indirect transmissions. The retransmitted RF signal proved to be intermittent. Also, one temperature channel was in a continuous state of saturation. (Later investigation showed that a thermistor lead had broken.) Since the thermistor leads also serve as the transmitting antenna for the implanted unit, RF field-strength measurements were made to determine the effect of the broken lead. The RF pulses from within the animal were very weak at the normal operating frequency of 54 MHz. The first harmonic at 108 MHz was nearly 20 dB stronger, but still weak. Therefore, the receiver in the collar was returned to the stronger 108 MHz signal and a single stage of RF amplification added. The previous tests were repeated. This time the retransmitter collar locked onto the pulses from the implanted transmitter with no loss in data.

Next, both the retransmitter and the implanted transmitter were tested for maximum range. As can be seen in figure 21, the test site was located in a heavily industrialized area with numerous power lines and metal buildings nearby. In A, the view is over a salt marsh toward the receiving station which was a metal building indicated by the arrow; the distance is 1 km. In B, the view is in the opposite direction which shows the instrumented dog and the investigator within a fenced ranging area. The implanted unit had a range of about 12 m. The AM receiver had an output bandwidth of 10 kHz and a sensitivity of 1 μV. The antenna, which was mounted on a 3-m mast, provided a gain of 6.5 dB. Because the transmitter, with its broken antenna lead, was operating in a greatly impeded mode, an estimate of maximum range was made. This estimate for the improved range was based on a previous comparison of the measured field strength at the normal operating frequency of 54 MHz, with that of the 108 MHz harmonic. This measurement, made with the transmitter placed within saline filled bags, showed the 54 MHz fundamental to be 42 dB greater than the 108 MHz harmonic. Additionally, simulated heart rate was transmitted successfully under these conditions over a distance of 175 m using the 54 MHz operating frequency and with receiver and antenna characteristics similar to those used in the later tests in which the lead was broken. These indications suggest that the range of a properly operating transmitter should be about 150 m. Improvement to a useful range greater than 200 m should be possible in an ideal, rural environment, particularly if a higher gain receiving antenna were used.

Range tests of the retransmitting system were conducted within the same industralized location. The retransmission system included the collar-mounted retransmitter, tracking receiver, cassette recorder, and interface unit. The receiver was located in a large one-story metal building with the antenna mounted on a 4-m mast placed on the roof. Total height above ground was 9 m. This antenna provided a gain of 14.5 dB. As before, a chart recorder was used to provide real-time measurement of heart rate and body temperatures using the demodulator's analog outputs. However, the tracking receiver, with its tone-burst output, drove the demodulator via the interface circuit. Again, the transmitted pulse train was recorded on one of the chart recorder channels. In addition to these real-time recordings, the receiver's output, along with voice commentary, was recorded on magnetic tape for subsequent analysis in the laboratory. Included were data taken while the dog was field-exercised on a leash. Two-way voice communications between the investigator in the field and the operator in the station were maintained during these tests. Next, the dog was placed within a chain-link fenced enclosure 1 km from the receiving station (fig. 21(b)). While in the 2-acre enclosure, the dog was allowed to roam about freely. Visual observation was maintained using a telescope. Finally, with the dog still in the enclosure, the receiver and a hand-held antenna (fig. 13) were taken to various remote locations to simulate tracking conditions.

These tests indicated that it was possible to retrieve data with a signal-to-noise ratio of unity at the receiver's output as viewed on an oscilloscope. This corresponds to the conditions present at about 80% or greater of the maximum tracking range. At this distance, the operator begins to experience problems hearing a tone distinct enough from background noise to allow effective tracking. The tracking system used was indicated by the manufacturer to have ground-to-ground tracking capability up to 18 km under ideal geographical conditions. Thus, the modified system should provide some physiological data at a distance perhaps as much as 14 km, but many things would limit that capability substantially.

Analysis of the accuracy of the temperature data gave a result closer to ±0.3° C rather than the desired ±0.1° C. This was not accounted for in the transmission link, since the intervals of the temperature pulses could be resolved repeatively within 200 μsec. The minimum pulse interval, representing 0° C, was 176 msec. Additionally, the temperature data are scanned within a second or so at each reading, including the high- and low-temperature calibrations. Thus, the resolution of the RF-transmission link, plus the continuous updating for drift during the temperature scan, should provide the desired ±0.1° C accuracy during the life of the unit (an unknown being the effects of moisture on the thermistors). However, at the time of these tests, the demodulator was set up to resolve increments of 1 msec, which does not provide the required resolution. More resolution can be had by extending the intervals at the transmitting end, or by increasing the resolution within the demodulator itself. Increasing the transmitted intervals would of course enhance the RF link, but at the expense of interrupting more of the beat-to-beat heart rate. On the other hand, the demodulator could be changed to provide the added resolution without changing the data format. The temperature cycle could be less frequent also. As indicated before, the system has sufficient flexibility within its basic design to allow a variety of easily implemented options for operation.

## CONCLUSION

The system described here provides heart rate and two body temperature measurements. The implantable transmitter is pulsed at each heartbeat with an interruption of 1-2 sec every 50 beats for transmission of temperature data. Low-powered, integrated circuits allow the system to be operated for a year or longer in animals that weigh a few kilograms or more. Direct transmission to an AM receiver operating at 54 MHz is possible at maximum ranges estimated to be 200 m. A retransmitter collar allows long-range transmission at 148 MHz. Radio-frequency links, originally designed for animal tracking, are used for retransmission. Physiological data can be recovered at distances within 80% of the maximum tracking range.

The system is designed to provide flexible capabilities, both at the transmitting and receiving ends. The transmitter's circuitry can be readily altered to sample more temperature sensors, and at different heartbeat intervals, or to transmit only the heartbeats or only the temperatures at the decade counts of heartbeats. The demodulator is microprocessor controlled so that software changes and added memory can accommodate transmitter modifications, along with linearization of data parameters.

# APPENDIX

# TEMPERATURE AND HEART RATE BIOTELEMETRY DEMODULATOR PROGRAM

TEMPERATURE AND HEART RATE BIOTELEMETRY DEMODULATOR

```
0000             0005 ;*************************************************
0000             0010 ;*                                               *
0000             0015 ;*          NASA AMES RESEARCH CENTER            *
0000             0020 ;*             MOUNTAIN VIEW,CA                  *
0000             0025 ;*                                               *
0000             0030 ;*          WRITTEN BY RAFAEL MIRANDA,E.E.       *
0000             0035 ;*                  JANUARY 1979                 *
0000             0040 ;*                                               *
0000             0045 ;*      NOTE: Z80 ASSEMBLY LANGUAGE CODE.        *
0000             0050 ;*                                               *
0000             0055 ;*************************************************
0000             0060 ;
0000             0065 ;INPUT AND OUTPUT PORT ASSIGNMENTS
0000             0070 ;
        0000     0075 PORT0:  EQU    0          ;ECG LED READOUT X10
        0001     0080 PORT1:  EQU    1          ;        X100
        0002     0085 PORT2:  EQU    2          ;T1 LED READOUT X1
        0003     0090 PORT3:  EQU    3          ;        X10
        0004     0095 PORT4:  EQU    4          ;T2 LED READOUT X1
        0005     0100 PORT5:  EQU    5          ;        X10
        0007     0105 PORT7:  EQU    7          ;FRONT PANEL IN PORT
0000             0110 ;                          AND TBG RESET FLAG.
0000             0115 ;
0000             0120 ;          ****************************
0000             0125 ;          *                          *
0000             0130 ;          *     C O N S T A N T S.   *
0000             0135 ;          *                          *
0000             0140 ;          ****************************
0000             0145 ;
        0000     0150 ZERO:   EQU    00H
        0001     0155 ONE:    EQU    01H
        0002     0160 TWO:    EQU    02H
        0008     0165 EIGHT:  EQU    08H
        0009     0170 NINE:   EQU    09H
        000A     0175 TEN:    EQU    10
        0011     0180 ELEVN:  EQU    11H
        0032     0185 FIFTY:  EQU    50
0000             0190 ;
0000             0195 ;SIXTY THOUSAND MILLISECONDS
        EA60     0200 SIXTY:  EQU    60000
        00FF     0205 INF:    EQU    0FFH        ;INFINITY
0000             0210 ;
0000             0215 ;TEMPERATURE PULSE WIDTH LIMITS
0000             0216 ;       IN MILLISECONDS
0000             0220 ;
        0012     0225 TMPLW:  EQU    18          ;LOW TEMP LIMIT
        0019     0230 TMPUW:  EQU    25          ;HIGH TEMP LIMIT
        0006     0235 ECGLW:  EQU    6           ;LOW LIMIT ECG
        000B     0240 ECGUW:  EQU    11          ;UPPER LIMIT ECG
0000             0245 ;
0000             0250 ;CALIBRATION TIME FOR 600 MSEC
        0058     0255 CALTL:  EQU    58H         ;CAL TIME LOW (BYTE)
        0002     0260 CALTH:  EQU    02H         ;CAL TIME HIGH (BYTE)
0000             0265 ;
0000             0270 ;NUMBER OF PULSES IN TEMPERATURE CYCLE
        000A     0275 FIVEDP: EQU    5*2
0000             0280 ;
0000             0285 ;16 BIT DIVISION SHIFT COUNT:
```

TEMPERATURE AND HEART RATE BIOTELEMETRY DEMODULATOR

```
       0011                        0290 SHFCNT: EQU    17
0000                               0295 ;INTERRUPT RESTART ROUTINES
0000                               0300 ;
0000                               0305 ;ENABLED BY HARDWARE ONLY
0000                               0310 ;
0000                               0315 ;*********************************************
0000                               0320 ;
0000                               0325 ;RSTRT: RE-START LOCATION  FORCED BY HITTING
0000                               0330 ;         THE RESET SWITCH IN THE FRONT
0000                               0335 ;         PANEL  OR  DURING  POWER-ON START UP
0000                               0340 ;         PROCEDURE.
0000                               0345 ;
0000                               0350 ;*********************************************
0000                               0355 ;
0000                               0360 ;ORG 0000H
0000                               0365 ;
0000  F3                           0370 RSTRT:  DI                   ;DISABLE HARDWARE INT.
0001  31 00 10                     0375         LD     SP,ERAM      ;STACK TO END OF RAM
0004  C3 38 00                     0380         JP     RESET
0007                               0385 ;
0007                               0390 ;
0007  00 00                        0395         DW     0
0009  00 00                        0400         DW     0
000B  00 00                        0405         DW     0
000D  00 00                        0410         DW     0
000F  00 00                        0415         DW     0
0011  00 00                        0420         DW     0
0013  00 00                        0425         DW     0
0015  00 00                        0430         DW     0
0017  00 00                        0435         DW     0
0019  00 00                        0440         DW     0
001B  00 00                        0445         DW     0
001D  00 00                        0450         DW     0
001F  00                           0455         DB     0
0020                               0460 ;
0020                               0465 ;*********************************************
0020                               0470 ;
0020                               0475 ;NEGRST
0020                               0480 ;         NEGATIVE GOING PULSE RESTART LOCATION
0020                               0485 ;         RST4 ... LOWEST PRIORITY
0020                               0490 ;         GETS FLAG AND VERIFIES IF THE LAST
0020                               0495 ;         FLAG WAS AN ECG FLAG OR A TEMPERATURE
0020                               0500 ;         FLAG
0020                               0505 ;
0020                               0510 ;         PRESERVES ALL REGISTERS
0020                               0515 ;
0020                               0520 ;*********************************************
0020                               0525 ;
0020  F5                           0530 NEGRST  PUSH   AF
0021  E5                           0535         PUSH   HL
0022  21 01 0C                     0540         LD     HL,DUMTM
0025  C3 63 00                     0545         JP     NEGCNT       ;EXIT TO CONTINUATOR
```

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OF POOR QUALITY

```
0028                    0555 ;**************************************************
0028                    0560 ;
0028                    0565 ;POSRST:
0028                    0570 ;          POSITIVE GOING PULSE RESTART LOCATION
0028                    0575 ;          RST5 ... PRIORITY=2 (1=HIGHEST)
0028                    0580 ;          STORES TIME INTERVAL BETWEEN PULSES
0028                    0585 ;          IN "TIME", TO BE USED IN COMPUTATIONS
0028                    0590 ;
0028                    0595 ;          PRESERVES ALL REGISTERS
0028                    0600 ;**************************************************
0028                    0605 ;
0028   F5               0610 POSRST: PUSH  AF
0029   E5               0615         PUSH  HL
002A   21 01 0C         0620         LD    HL,DUMTM
002D   C3 8C 00         0625         JP    POSCNT     ;EXIT TO CONTINUATOR
0030                    0630 ;
0030                    0635 ;
0030                    0640 ;
0030                    0645 ;
0030                    0650 ;
0030                    0655 ;**************************************************
0030                    0660 ;
0030                    0665 ;TBGRST:
0030                    0670 ;         TIME BASE GENERATOR RESTART LOCATION
0030                    0675 ;         RST6 ... HIGHEST PRIORITY
0030                    0680 ;         INCREMENTS "DUMTM" BY ONE
0030                    0685 ;
0030                    0690 ;         PRESERVES ALL REGISTERS
0030                    0695 ;
0030                    0700 ;**************************************************
0030                    0705 ;
0030   F5               0710 TBGRST: PUSH  AF
0031   E5               0715         PUSH  HL
0032   21 01 0C         0720         LD    HL,DUMTM
0035   C3 BA 00         0725         JP    TBCNT      ;EXIT TO CONTINUATOR
```

TEMPERATURE AND HEART RATE BIOTELEMETRY DEMODULATOR

```
0038                    0735 ;**********************************************
0038                    0740 ;
0038                    0745 ;RESET:
0038                    0750 ;          RSTRT CONTINUATOR
0038                    0755 ;          INITIALIZES FRONT PANEL LED DISPLAYS
0038                    0760 ;          TO
0038                    0765 ;               000     00.0    00.0
0038                    0770 ;          READS FRONT PANEL SWITCHES
0038                    0775 ;
0038                    0780 ;**********************************************
0038                    0785 ;
0038  DB 07             0790 RESET:   IN     A,PORT7    ;READ SWITCHES
003A  47                0795          LD     B,A
003B  E6 01             0800          AND    ONE
003D  CA 9C 02          0805          JP     Z,CAL      ;IF PORT7=1..CALIBRATE
0040                    0810 ;
0040  AF                0815 OPRTE:   XOR    A          ;CLEAR ACC. AND CY
0041  21 00 0C          0820          LD     HL,RAM     ;RAM ORG. TO HL
0044  06 13             0825          LD     B,RAMEND
0046                    0830 ;
0046  77                0835 CLRLP:   LD     (HL),A     ;CLEAR RAM
0047  05                0840          DEC    B
0048  23                0845          INC    HL
0049  B8                0850          CP     B          ;WAIT UNTIL B=0H
004A  C2 46 00          0855          JP     NZ,CLRLP
004D                    0860 ;
004D                    0865 ;CLEAR ALL LED DISPLAYS
004D                    0870 ;
004D  D3 00             0875          OUT    PORT0,A
004F  D3 01             0880          OUT    PORT1,A
0051  D3 02             0885          OUT    PORT2,A
0053  D3 03             0890          OUT    PORT3,A
0055  D3 04             0895          OUT    PORT4,A
0057  D3 05             0900          OUT    PORT5,A
0059                    0905 ;
0059                    0910 ;RESET REAL TIME CLOCK
0059                    0915 ;
0059  D3 07             0920          OUT    PORT7,A
005B  3E 01             0925          LD     A,ONE      ;SET UP START OF CLOCK
005D  D3 07             0930          OUT    PORT7,A    ;START 1 MSEC TIMER
005F                    0935 ;
005F  FB                0940          EI                ;ALLOW HARDWARE INT.
0060                    0945 ;
0060  C3 60 00          0950 WAIT:    JP     WAIT       ;WAIT FOR AN INTERRUPT
```

```
0063                   0960 ;**********************************************************
0063                   0965 ;
0063                   0970 ;NEGCNT:
0063                   0975 ;          CONTINUATOR ROUTINE TO NEGRST
0063                   0980 ;          CHECKS TIME INTERVAL BETWEEN PULSES
0063                   0985 ;          IF IT CHECKS WITHIN THE PRE-SET LIMITS
0063                   0990 ;          UPDATES THE ECG OR TEMP. FLAG
0063                   0995 ;
0063                   1000 ;**********************************************************
0063                   1005 ;
0063  3E 12            1010 NEGCNT: LD    A,TMPLW    ;GET TEMP LOWER LIMIT
0065  BE               1015         CP    (HL)
0066  D2 6F 00         1020         JP    NC,NXTST   ;IF G.T. CONTINUE
0069  7E               1025         LD    A,(HL)     ;TEST UPPER LIMIT
006A  FE 19            1030         CP    TMPUW      ;IF L.T GO TO TEMPF
006C  DA 7F 00         1035         JP    C,TEMPF    ;IF NOT CONTINUE
006F                   1040 ;
006F  3E 06            1045 NXTST:  LD    A,ECGLW    ;GET ECG LOWER LIMIT
0071  BE               1050         CP    (HL)
0072  D2 7B 00         1055         JP    NC,NFLG    ;EXIT IF SMALLER
0075  7E               1060         LD    A,(HL)
0076  FE 0B            1065         CP    ECGUW      ;IF L.T. GO TO ECGF
0078  DA 84 00         1070         JP    C,ECGF     ;IF NOT CONTINUE
007B                   1075 ;
007B  AF               1080 NFLG    XOR   A          ;CURRENT FLAG=0
007C  C3 86 00         1085         JP    ENDNEG
007F                   1090 ;
007F  3E 02            1095 TEMPF:  LD    A,TWO      ;PULSE W/IN TEMP LIMIT
0081  C3 86 00         1100         JP    ENDNEG
0084                   1105 ;
0084  3E 01            1110 ECGF:   LD    A,ONE      ;PULSE W/IN TEMP LIMIT
0086                   1115 ;
0086  2B               1120 ENDNEG: DEC   HL
0087  77               1125         LD    (HL),A     ;STORE RESULT IN "FLAG"
0088                   1130 ;
0088  E1               1135         POP   HL
0089  F1               1140         POP   AF
008A  FB               1145         EI               ;ALLOW HIGHER
008B                   1150 ;                        PRIORITY INTERRUPTS
008B                   1155 ;
008B  C9               1160         RET
```

```
008C                    1170 ;*******************************************
008C                    1175 ;
008C                    1180 ;POSCNT:
008C                    1185 ;          CONTINUATOR ROUTINE TO POSRST
008C                    1190 ;          STORES TEMPORARY VALUE OF "DUMTM"
008C                    1195 ;          INTO "TIME". CLEARS TEMPORARY VALUE
008C                    1200 ;          OF 'DUMTM'; COMPUTES H.R. OR TEMP
008C                    1205 ;
008C                    1210 ;          CHECKS 'BUSY' FLAG (IF 'BUSY', RETURNS
008C                    1215 ;          WAITS FOR INTERRUPTS
008C                    1220 ;
008C                    1225 ;*******************************************
008C                    1230 ;
008C   D3 07            1235 POSCNT: OUT   PORT7,A    ;RESET 1 MSEC TIMER
008E   7E               1240         LD    A,(HL)     ;GET LOW BYTE OF TIME
008F   32 02 0C         1245         LD    (TIME),A   ;STORE IT IN "TIME"
0092   AF               1250         XOR   A
0093   77               1255         LD    (HL),A     ;CLEAR TEMPO. STORAGE
0094   23               1260         INC   HL
0095   7E               1265         LD    A,(HL)     ;DO THE SAME FOR
0096   32 03 0C         1270         LD    (TIME+1),A;HIGH ORDER BYTE
0099   AF               1275         XOR   A
009A   77               1280         LD    (HL),A     ;CLEAR TEMPO. STORAGE
009B                    1285 ;
009B   3A 12 0C         1290         LD    A,(BUSY)   ;CHECK IF BUSY
009E   FE 01            1295         CP    ONE        ;IF NOT DONE RETURN
00A0   C2 A7 00         1300         JP    NZ,SKIPIT ;IF DONE GO TO SKIPIT
00A3                    1305 ;
00A3   E1               1310         POP   HL
00A4   F1               1315         POP   AF
00A5                    1320 ;
00A5   FB               1325         EI               ;ALLOW HARDWARE INT.
00A6   C9               1330         RET
00A7                    1335 ;
00A7   E1               1340 SKIPIT: POP   HL
00A8   F1               1345         POP   AF         ;FLAG WAS DONE
00A9   FB               1350         EI               ;ALLOW TBG TO INT
00AA                    1355 ;
00AA   3A 00 0C         1360 CHLOUT: LD    A,(FLAG)
00AD   47               1365         LD    B,A        ;PREVENT CHANGING THE
00AE   E6 01            1370         AND   ONE        ;TIME VALUES
00B0   C2 C7 00         1375         JP    NZ,ECGSUB ;IF FLAG=1 THEN ECGSUB
00B3                    1380 ;
00B3   78               1385         LD    A,B
0084   E6 02            1390         AND   TWO        ;TEMP CALCULATION?
00B6   C2 64 01         1395         JP    NZ,TMPSUB ;IF NOT RETURN TO WAIT
00B9                    1400 ;
00B9   C9               1405         RET
```

TEMPERATURE AND HEART RATE BIOTELEMETRY DEMODULATOR

```
00BA                 1415 ;************************************************
00BA                 1420 ;
00BA                 1425 ;TBCNT:
00BA                 1430 ;       CONTINUATOR ROUTINE TO TBGRST
00BA                 1435 ;       INCREMENTS TEMPORARY STORAGE FOR TIME
00BA                 1440 ;       BY ONE MILLISECOND. RETURNS
00BA                 1445 ;
00BA                 1450 ;       ALL REGISTERS PRESERVED
00BA                 1455 ;
00BA                 1460 ;************************************************
00BA                 1465 ;
00BA                 1470 ;
00BA   3E 01         1475 TBCNT:  LD     A,ONE       ;INCREMENT "DUMTM"
00BC   86            1480         ADD    (HL)        ;BY ONE
00BD   77            1485         LD     (HL),A      ;STORE IT
00BE   23            1490         INC    HL          ;INCR. HIGH ORDER BYTE
00BF   3E 00         1495         LD     A,ZERO
00C1   8E            1500         ADC    (HL)        ;ADD CY TO (HIGH) BYTE
00C2   77            1505         LD     (HL),A      ;BYTE AND STORE IT
00C3                 1510 ;
00C3   E1            1515         POP    HL
00C4   F1            1520         POP    AF
00C5                 1525 ;
00C5   FB            1530         EI                 ;ALLOW HARDWARE INT.
00C6   C9            1535         RET
```

```
00C7                 1545 ;*************************************************
00C7                 1550 ;
00C7                 1555 ;ECGSUB:
00C7                 1560 ;         COUNTS NUMBER OF ECG PULSES:
00C7                 1565 ;         CALCULATES HEART RATE
00C7                 1570 ;         CONVERTS BINARY RESULT TO BCD
00C7                 1575 ;         OUTPUTS RESULT TO FRONT PANEL
00C7                 1580 ;         RETURNS TO WAIT FOR A NEW
00C7                 1585 ;         INSTRUCTION OR INTERRUPT
00C7                 1590 ;
00C7                 1595 ;*************************************************
00C7                 1600 ;
00C7   3A 09 0C      1605 ECGSUB:  LD    A,(ECGCNT);GET NUMBER OF R WAVES
00CA   FE 00         1610          CP    ZERO       ;IS IT THE FIRST BEAT?
00CC   C2 DE 00      1615          JP    NZ,CONT1   ;IF YES, CONTINUE
00CF                 1620 ;
00CF                 1625 ;FIRST BEAT INDICATES A T CYCLE OR ECG BEAT
00CF                 1630 ;
00CF   3A 06 0C      1635          LD    A,(CTRTEM);GET # OF TEMP. PULSES
00D2   FE 0A         1640          CP    FIVEDP     ;IS # OF PULSES
00D4                 1645 ;EQUAL TO FIVEP?. IF YES GO TO IMPOUT
00D4                 1650 ;TO CALCULATE TEMPERATURES & OUTPUT RESULTS
00D4   CA C8 01      1655          JP    Z,IMPOUT
00D7                 1660 ;
00D7   AF            1665          XOR   A          ;NOT A TEMP CYCLE
00D8   32 06 0C      1670          LD    (CTRTEM),A;RESET TEMP COUNTER
00DB   C3 E4 00      1675          JP    GOBACK
00DE                 1680 ;
00DE   FE 32         1685 CONT1:   CP    FIFTY      ;50 R WAVES COUNTED?
00E0   C2 E9 00      1690          JP    NZ,SKPCLR ;IF NOT CONTINUE
00E3   AF            1695          XOR   A          ;CLEAR R WAVE COUNT
00E4                 1700 ;
00E4   3C            1705 GOBACK:  INC   A
00E5   32 09 0C      1710          LD    (ECGCNT),A;STORE VALUE OF ONE
00E8   C9            1715          RET
00E9                 1720 ;
00E9   3C            1725 SKPCLR:  INC   A          ;UPDATE R WAVE COUNT
00EA   32 09 0C      1730          LD    (ECGCNT),A;STORE IT
00ED                 1735 ;
00ED                 1740 ;START CALCULATING HEART RATE
00ED                 1745 ;
00ED   CD 25 01      1750          CALL  BSYDNE     ;SET BUSY FLAG
00F0   11 60 EA      1755          LD    DE,SIXTY   ;DIVIDEND=60000 MSEC.
00F3                 1760 ;
00F3                 1765 ;DIVIDE 60000 MSEC BY RR INTERVAL IN "TIME"
00F3                 1770 ;
00F3   CD 37 01      1775          CALL  DIVIDE     ;GET BINARY HEART RATE
00F6   CD 71 01      1780          CALL  BINBCD     ;BINARY TO DECIMAL
00F9                 1785 ;
00F9   79            1790          LD    A,C        ;GET H.R. X 1
00FA   D3 00         1795          OUT   PORT0,A    ;LEAST SIGNIFICANT LED
00FC   78            1800          LD    A,B        ;Get Heart rate X 100
00FD   D3 01         1805          OUT   PORT1,A    ;most significant HR
00FF   AF            1810          XOR   A          ;CLEAR BUSY FLAG
0100   32 12 0C      1815          LD    (BUSY),A   ;STORE IT
0103                 1820 ;
0103   C9            1825          RET
```

```
TEMPERATURE AND HEART RATE BIOTELEMETRY DEMODULATOR

0104                1835 ;*********************************************
0104                1840 ;*                                            *
0104                1845 ;* TMPSUB:                                    *
0104                1850 ;*          STORES TEMPERATURE INTERVAL IN    *
0104                1855 ;*          SEQUENCE: T0(REF),T1,T2,T50(REF)  *
0104                1860 ;*          CLEARS R WAVE COUNT               *
0104                1865 ;*  ,                                         *
0104                1870 ;*********************************************
0104                1875 ;
0104  CD 25 01      1880 TMPSUB: CALL  BSYDNE
0107                1885 ;
0107  3A 06 0C      1890         LD    A,(CTRTEM);GET TEMP. CYCLE COUNT
010A  3C            1895         INC   A
010B  3C            1900         INC   A          ;UPDATE IT BY TWO
010C  32 06 0C      1905         LD    (CTRTEM),A;STORE IT
010F                1910 ;
010F  21 08 0C      1915         LD    HL,SAVTIM ;MSAVE IT
0112  85            1920         ADD   L
0113  6F            1925         LD    L,A        ;UPDATE T CYCLE PTR
0114  3A 03 0C      1930         LD    A,(DIVTM)
0117  77            1935         LD    (HL),A     ;STORE TIME INTERVAL
0118                1940 ;
0118  23            1945         INC   HL
0119  3A 04 0C      1950         LD    A,(DIVTM+1)
011C  77            1955         LD    (HL),A     ;HIGH ORDER BYTE
011D  AF            1960         XOR   A          ;CLEAR ECG COUNT
011E  32 09 0C      1965         LD    (ECGCNT),A
0121                1970 ;
0121  32 12 0C      1975         LD    (BUSY),A
0124                1980 ;
0124  C9            1985         RET
0125                1990 ;
0125                1995 ;*********************************************
0125                2000 ;*                                            *
0125                2005 ;* BSYDNE:                                    *
0125                2010 ;*         SETS UP BUSY FLAG                  *
0125                2015 ;*         MOVES TEMPORARY TIME INTERVAL      *
0125                2020 ;*         TO "DIVTM"..TIME TO BE USED IN     *
0125                2025 ;*         COMPUTATIONS                       *
0125                2030 ;*                                            *
0125                2035 ;*********************************************
0125                2040 ;
0125  3E 01         2045 BSYDNE  LD    A,ONE      ;SET UP BUSY FLAG
0127                2050 ;
0127  32 12 0C      2055         LD    (BUSY),A
012A  21 02 0C      2060         LD    HL,TIME
012D  7E            2065         LD    A,(HL)     ;GET LOW ORDER TIME
012E  32 03 0C      2070         LD    (DIVTM),A ;STORE IT IN PERMNT.
0131  23            2075         INC   HL
0132  7E            2080         LD    A,(HL)     ;HIGH ORDER TIME
0133  32 04 0C      2085         LD    (DIVTM+1),A;STORE IT
0136                2090 ;
0136  C9            2095         RET
```

## TEMPERATURE AND HEART RATE BIOTELEMETRY DEMODULATOR

```
0137                 2105 ;*********************************************
0137                 2110 ;*                                            *
0137                 2115 ;*  DIVIDE:                                   *
0137                 2120 ;*        DIVIDES A 16 BIT DIVISOR IN THE BC  *
0137                 2125 ;*        REGISTERS BY A 16 BIT DIVIDEND IN   *
0137                 2130 ;*        THE DE REGS.  RESULT IS RETURNED    *
0137                 2135 ;*        IN THE DE & HL REGISTERS.           *
0137                 2140 ;*                                            *
0137                 2145 ;*********************************************
0137                 2150 ;
0137  21 05 0C       2155 DIVIDE: LD    HL,BNUM    ;COUNTER ADDRESS
013A  36 11          2160         LD    (HL),SHFCNT;START SHIFT COUNT
013C  01 00 00       2165         LD    BC,ZERO
013F                 2170 ;
013F  7B             2175 DLOOP:  LD    A,E        ;ROTATE DIVISOR
0140  17             2180         RLA              ;LEFT ONE BIT
0141  5F             2185         LD    E,A
0142  7A             2190         LD    A,D
0143  17             2195         RLA
0144  56             2200         LD    D,(HL)     ;DECREMENT BIT COUNTER
0145  15             2205         DEC   D
0146  72             2210         LD    (HL),D
0147  57             2215         LD    D,A
0148  CA 6F 01       2220         JP    Z,ENDDIV   ;RETURN IF COUNT=0
014B                 2225 ;
014B  79             2230         LD    A,C        ;ROTATE RESULT
014C  17             2235         RLA              ;LEFT ONE BIT
014D  4F             2240         LD    C,A
014E  78             2245         LD    A,B
014F  17             2250         RLA
0150  47             2255         LD    B,A
0151  21 03 0C       2260         LD    HL,DIVIN   ;GET DIVIDEND ADDR.
0154                 2265 ;
0154  79             2270         LD    A,C        ;SUBTRACT LOW
0155  96             2275         SUB   (HL)       ;ORDER BYTE OF
0156  4F             2280         LD    C,A        ;DIVIDEND
0157  2C             2285         INC   L
0158  78             2290         LD    A,B        ;SUBTRACT HIGH
0159  9E             2295         SBC   (HL)       ;ORDER BYTE
015A                 2300 ;
015A  47             2305         LD    B,A        ;NO BORROW?
015B  D2 66 01       2310         JP    NC,DSKIP   ;IF YES ADDRESS LO BYTE
015E  2D             2315         DEC   L
015F  79             2320         LD    A,C        ;ADD DIVIDEND BACK
0160  86             2325         ADD   (HL)
0161  4F             2330         LD    C,A
0162  2C             2335         INC   L
0163  78             2340         LD    A,B
0164  8E             2345         ADC   (HL)
0165  47             2350         LD    B,A
0166                 2355 ;
0166  21 05 0C       2360 DSKIP   LD    HL,BNUM    ;RESTORE ADDR. OF CNTR
0169  9F             2365         SBC   A          ;COMPLEMENT CARRY
016A  DE 80          2370         SBC   080H
016C  C3 3F 01       2375         JP    DLOOP      ;REPEAT
016F                 2380 ;
016F  EB             2385 ENDDIV: EX    DE,HL      ;STORE RESULT IN HL
0170  C9             2390         RET
```

```
0171                    2395 ;************************************************
0171                    2400 ;                                                ;
0171                    2405 ; BINBCD:                                        ;
0171                    2410 ;          16 BIT BINARY TO BCD CONVERSION       ;
0171                    2415 ;          BINARY NUMBER IN HL:                  ;
0171                    2420 ;             H=HIGH  L=LOW ORDER BYTE           ;
0171                    2425 ;          RESULT:  A=X10,000 B=X100  C=X1       ;
0171                    2430 ;                                                ;
0171                    2435 ;************************************************
0171                    2440 ;
0171  1E 11             2445 BINBCD: LD    E,ELEVN    ;SET BIT COUNTER
0173  CD 84 01          2450         CALL  BCD
0176  4F                2455         LD    C,A        ;SAVE L.SIG. BCD BYTE
0177  1E 11             2460         LD    E,ELEVN
0179  C3 7E 01          2465         JP    BNEXT
017C                    2470 ;
017C  1E 09             2475         LD    E,NINE
017E  CD 84 01          2480 BNEXT:  CALL  BCD
0181  47                2485         LD    B,A
0182  7D                2490         LD    A,L
0183  C9                2495         RET              ;DONE
0184                    2500 ;
0184  AF                2505 BCD:    XOR   A
0185  1D                2510 CVT:    DEC   E
0186  C8                2515         RET   Z
0187  29                2520         ADD   HL,HL
0188  8F                2525         ADC   A
0189                    2530 ;
0189  27                2535         DAA
018A  D2 85 01          2540         JP    NC,CVT
018D  23                2545         INC   HL
018E  C3 85 01          2550         JP    CVT
```

```
0191                2560 ;************************************************
0191                2565 ;                                                ;
0191                2570 ; MULT:                                          ;
0191                2575 ;          16 BIT BY 8 BIT MULTIPLICATION        ;
0191                2580 ;          BC=MULTIPLICAND   X H(MULTIPLIER)=    ;
0191                2585 ;          DE(PRODUCT). BC X H=DE REGISTERS      ;
0191                2590 ;                                                ;
0191                2595 ;************************************************
0191                2600 ;
0191   11 00 00     2605 MULT:    LD     DE,ZERO      ;ERASE PRODUCT
0194                2610 ;
0194   B7           2615 MLOOP:   OR     A            ;CLEAR CARRY
0195   7C           2620          LD     A,H
0196   1F           2625          RRA
0197   67           2630          LD     H,A
0198                2635 ;
0198                2640 ;IF MULTIPLIER BIT=1,ADD MPCND TO PRODCT
0198   DC A7 01     2645          CALL   C,MADD
019B                2650 ;
019B   7C           2655          LD     A,H          ;EXIT IF MPIER IS 0
019C   A7           2660          AND    A
019D   C8           2665          RET    Z            ;RETURN
019E                2670 ;
019E   79           2675          LD     A,C          ;  OTHERWISE
019F   17           2680          RLA                 ;     SHIFT
01A0   4F           2685          LD     C,A          ; MULTIPLICAND
01A1   78           2690          LD     A,B          ;   LEFT
01A2   17           2695          RLA                 ;    AND
01A3   47           2700          LD     B,A          ;    REPEAT
01A4   C3 94 01     2705          JP     MLOOP
01A7                2710 ;
01A7   79           2715 MADD:    LD     A,C          ;ADD PARTIAL
01A8   83           2720          ADD    E            ;PRODUCT
01A9   5F           2725          LD     E,A
01AA   78           2730          LD     A,B
01AB   8A           2735          ADC    D
01AC   57           2740          LD     D,A
01AD   C9           2745          RET
```

TEMPERATURE AND HEART RATE BIOTELEMETRY DEMODULATOR

```
01AE                    2755 ;**************************************************
01AE                    2760 ;                                                  ;
01AE                    2765 ; MPYX10:                                          ;
01AE                    2770 ;          MULTIPLIES DE REGISTER BY 10            ;
01AE                    2775 ;          AND PLACES RESULT IN DE                 ;
01AE                    2780 ;                                                  ;
01AE                    2785 ;          REGISTERS AFFECTED: HL,AB,DE            ;
01AE                    2790 ;                                                  ;
01AE                    2795 ;**************************************************
01AE                    2800 ;
01AE  6B                2805 MPYX10: LD    L,E         ;MOVE HL TO DE
01AF  62                2810         LD    H,D
01B0  06 FD             2815         LD    B,-3        ;SET UP COUNT
01B2  B7                2820         OR    A           ;CLEAR CARRY
01B3                    2825 ;
01B3  04                2830 LOOP10: INC   B
01B4  7D                2835         LD    A,L
01B5  17                2840         RLA
01B6  6F                2845         LD    L,A         ;MULTIPLY RESULT
01B7  7C                2850         LD    A,H         ;    BY
01B8  17                2855         RLA               ;  EIGHT
01B9  67                2860         LD    H,A
01BA  78                2865         LD    A,B
01BB  C2 B3 01          2870         JP    NZ,LOOP10 ;X8 IN HL REG.
01BE                    2875 ;
01BE  B7                2880         OR    A           ;MULTIPLY
01BF  7B                2885         LD    A,E         ; AGAIN
01C0  17                2890         RLA               ;    BY
01C1  5F                2895         LD    E,A         ;  TWO
01C2  7A                2900         LD    A,D
01C3  17                2905         RLA
01C4  57                2910         LD    D,A         ;X2 IN DE REG.
01C5  19                2915         ADD   HL,DE       ;ADD X8 + X2
01C6  EB                2920         EX    DE,HL       ;RESULT TO DE
01C7                    2925 ;
01C7  C9                2930         RET
```

```
01C8                  2940 ;*******************************************
01C8                  2945 ;                                          ;
01C8                  2950 ; TMPOUT:                                  .
01C8                  2955 ;        COMPUTES T1 AND T2 (UNKNOWN):     ;
01C8                  2960 ;                                          ;
01C8                  2965 ; T(UNKNOWN)=((T(UNKNOWN)-T0)/(T50-T0))*50 ;
01C8                  2970 ;                                          ,
01C8                  2975 ;        IF T50 WAS NOT UPDATED OR         ;
01C8                  2980 ,        IF T(UNKNOWN)-T0 IS NEGATIVE OR   ;
01C8                  2985 ;        IF RESULT IS G.T  50 IT ABORTS    ;
01C8                  2990 ;                                          ;
01C8                  2995 ;        OUTPUTS RESULTS TO FRONT PANEL    ;
01C8                  3000 ;                                          ;
01C8                  3005 ;        DISABLES INTERRUPTS DURING CRITICAL ;
01C8                  3010 ;        CALCULATIONS                      ;
01C8                  3015 ;                                          ;
01C8                  3020 ;*******************************************
01C8                  3025 ;
01C8   3E 01          3030 TMPOUT: LD    A,ONE      ;SET BUSY FLAG
01CA   32 12 0C       3035         LD    (BUSY),A   ;STORE IT
01CD   32 09 0C       3040         LD    (ECGCNT),A;ECG COUNT=1
01D0   AF             3045         XOR   A          ;CLEAR CARRY
01D1   32 06 0C       3050         LD    (CTRTEM),A;TEMP CTR=0
01D4                  3055 ;
01D4   21 10 0C       3060         LD    HL,TEMPST+6; GET T50(REF)
01D7   7E             3065         LD    A,(HL)     ;A HAS T50
01D8   FE 00          3070         CP    ZERO       ;UPDATED?
01DA   CC 1D 02       3075         CALL  Z,TEST2    ;IF NOT,RETURN
01DD                  3080 ;
01DD   21 0A 0C       3085         LD    HL,TEMPST  ;GET T0 (REF)
01E0   4E             3090         LD    C,(HL)     ;C HAS LOW ORDER BYT
01E1   96             3095         SUB   (HL)
01E2   32 03 0C       3100         LD    (DIVTM),A  ;PARTIAL RESULT
01E5   21 11 0C       3105         LD    HL,TEMPST+7;BYTE 2
01E8   7E             3110         LD    A,(HL)
01E9   21 0B 0C       3115         LD    HL,TEMPST+1;T0 (REF) HIGH
01EC   F3             3120         DI
01ED   46             3125         LD    B,(HL)
01EE   9E             3130         SBC   (HL)       ;T50-T0 HIGH ORDER
01EF   DA 0B 02       3135         JP    C,CLRFLG   ;IF NEGATIVE EXIT
01F2   32 04 0C       3140         LD    (DIVTM+1),A;STORE IT
01F5   23             3145         INC   HL         ;GET T1 POINTER
01F6   C5             3150         PUSH  BC
01F7                  3155 ;
01F7   CD 27 02       3160         CALL  TMPGO      ;CALCULATE T1
01FA   D3 02          3165         OUT   PORT2,A    ;T1 TO LED display
01FC   78             3170         LD    A,B        ;Most significant
01FD   D3 03          3175         OUT   PORT3,A    ;result to T1
01FF   C1             3180         POP   BC
0200                  3185 ;
0200   21 0E 0C       3190         LD    HL,TEMPST+4,GET T2 POINTER
0203   CD 27 02       3195         CALL  TMPGO      ;CALCULATE T2
0206                  3200 ;
0206   D3 04          3205         OUT   PORT4,A    ;L.S. BCD out
0208   78             3210         LD    A,B        ;Most significant
0209   D3 05          3215         OUT   PORT5,A    ;result to T2
```

```
020B                   3225 ;                *****************************
020B                   3230 ;                *                           *
020B                   3235 ;                *     TMPOUT (CONTINUATION)  *
020B                   3240 ;                *                           *
020B                   3245 ;                *****************************
020B                   3250 ;
020B   FB              3255 CLRFLG: EI
020C   AF              3260          XOR   A            ;CLEAR BUSY FLAG
020D   32 10 0C        3265          LD    (TEMPST+6),A;CLEAR T50(REF)
0210   32 11 0C        3270          LD    (TEMPST+7),A
0213   32 12 0C        3275          LD    (BUSY),A
0216   C9              3280          RET                ;RETURN TO MAIN PROG.
0217                   3285 ;
0217                   3290 ;
0217   21 0B 02        3295 EXEND:   LD    HL,CLRFLG ;EXCHANGE
021A   C1              3300          POP   BC           ;TOP OF STACK
021B   E3              3305          EX    (SP),HL      ;& RETURN TO CLR FLG
021C   C9              3310          RET
021D                   3315 ;
021D                   3320 ;
021D   4F              3325 TEST2:   LD    C,A          ;STORE HIGH BYTE
021E   23              3330          INC   HL
021F   7E              3335          LD    A,(HL)
0220   C6 00           3340          ADD   ZERO         ;TEST LOW BYTE
0222   CA 0B 02        3345          JP    Z,CLRFLG
0225   79              3350          LD    A,C          ;RESTORE (HIGH) BYTE
0226   C9              3355          RET
0227                   3360 ;
0227                   3365 ;
0227   AF              3370 TMPGO:   XOR   A            ;CALCULATE TEMP
0228   7E              3375          LD    A,(HL)
0229   91              3380          SUB   C
022A   4F              3385          LD    C,A
022B                   3390 ;
022B   23              3395          INC   HL           ;SUBTRACT
022C   7E              3400          LD    A,(HL)       ;T50(REF)-T0(REF)
022D   98              3405          SBC   B
022E   DA 17 02        3410          JP    C,EXEND      ;IF NEGATIVE RETURN
0231   47              3415          LD    B,A          ;TEMP STORE
0232                   3420 ;
0232   21 03 0C        3425          LD    HL,DIVTM
0235   7E              3430          LD    A,(HL)
0236   3C              3435          INC   A
0237   91              3440          SUB   C            ;BC=T1 OR T2-T0(REF)
0238   23              3445          INC   HL
0239   7E              3450          LD    A,(HL)
023A   98              3455          SBC   B            ;(T50-T0+1)-(T1-T0)
023B   DA 17 02        3460          JP    C,EXEND      ;IF NEG.RETURN
023E   26 32           3465          LD    H,FIFTY      ;DEGREES
0240                   3470 ;
0240   CD 91 01        3475          CALL  MULT         ;CALCULATE T1 OR T2
0243   CD 4B 02        3480          CALL  DIVSP
0246   CD 71 01        3485          CALL  BINBCD
0249   7D              3490          LD    A,L          ;Result X1
024A   C9              3495          RET
```

```
024B                     3505 ;*******************************************
024B                     3510 ;                                           ;
024B                     3515 ;DIVSP-                                     ;
024B                     3520 ;      CALLED BY TEMPGO, IT CALCULATES      ;
024B                     3525 ;      ((T1 OR T2)-T0(REF)*50)/(T50-T0)     ;
024B                     3530 ;      PRECISE TO ONE DECIMAL PLACE XX.X    ;
024B                     3535 ;      DOES NOT ROUND OFF RESULT            ;
024B                     3540 ;                                           ;
024B                     3545 ;*******************************************
024B                     3550 ;
024B                     3555 ;
024B   2A 03 0C          3560 DIVSP:  LD     HL,(DIVTM);GET DIVISOR
024E                     3565 ;
024E                     3570 ;DIVIDE T-T0*50/T50-T0
024E                     3575 ;
024E   CD 6B 02          3580         CALL   DIV16Q
0251   E5                3585         PUSH   HL          ;SAVE REMAINDER
0252                     3590 ;
0252   CD AE 01          3595         CALL   MPYX10      ;DE(RESULT)=DEX10
0255   E1                3600         POP    HL          ;SAVE RESULT
0256   D5                3605         PUSH   DE
0257   EB                3610         EX     DE,HL       ;REMAINDER IN DE
0258   CD AE 01          3615         CALL   MPYX10      ;REMAINDERX10 IN DE
025B                     3620 ;
025B   2A 03 0C          3625         LD     HL,(DIVTM);DIVIDE AGAIN
025E   CD 6B 02          3630         CALL   DIV16Q      ;RESULT IN DE REG
0261   EB                3635         EX     DE,HL       ;RESULT TO HL
0262                     3640 ;
0262   D1                3645         POP    DE          ;GET FIRST QUOTIENT
0263                     3650 ;
0263                     3655 ;ADD QUOTIENT TO RESULT
0263                     3660 ;
0263   19                3665         ADD    HL,DE
0264   3E 01             3670         LD     A,ONE
0266   BA                3675         CP     D
0267   D0                3680         RET    NC          ;RETURN IF POSITIVE
0268   C3 17 02          3685         JP     EXEND
```

```
026B                   3695 ;*******************************************
026B                   3700 ;                                           ;
026B                   3705 ; DIV16Q:                                   ;
026B                   3710 ;         CALLED BY DIVSP: IT CALCULATES    ;
026B                   3715 ;         T(UNKNOWN) BY DIVIDING DE(DIVIDEND) ;
026B                   3720 ;         BY HL (DIVISOR AND REMAINDER)     ;
026B                   3725 ;         DE=RESULT                         ;
026B                   3730 ;                                           ;
026B                   3735 ;*******************************************
026B                   3740 ;
026B   22 07 0C        3745 DIV16Q: LD    (TEMP),HL ;SAVE DIVISOR
026E   21 05 0C        3750         LD    HL,BNUM   ;STORE BIT COUNT
0271   36 11           3755         LD    (HL),ELEVN
0273   01 00 00        3760         LD    BC,ZERO   ;INIT RESULT
0276   C5              3765         PUSH  BC
0277                   3770 ;
0277   7B              3775 LOOPD:  LD    A,E       ;GET LWR DIVIDND BYT
0278   17              3780         RLA
0279   5F              3785         LD    E,A       ;SHIFT DIVIDEND
027A   7A              3790         LD    A,D
027B   17              3795         RLA             ;LEFT ONE BIT
027C   57              3800         LD    D,A
027D   35              3805         DEC   (HL)      ;DECR COUNT
027E   E1              3810         POP   HL        ;RESTORE TEMP RESULT
027F   C8              3815         RET   Z         ;ZERO COUNT?
0280   3E 00           3820         LD    A,ZERO
0282   CE 00           3825         ADC   ZERO      ;ADD CARRY
0284   29              3830         ADD   HL,HL     ;SHIFT LEFT ONCE
0285   44              3835         LD    B,H       ;HL TO ACC.
0286   85              3840         ADD   L
0287   2A 07 0C        3845         LD    HL,(TEMP) ;GET DIVISOR ADDR
028A   95              3850         SUB   L         ;SUBTRACT IT
028B   4F              3855         LD    C,A
028C   78              3860         LD    A,B       ;TEMP RESULT
028D   9C              3865         SBC   H
028E   47              3870         LD    B,A
028F   C5              3875         PUSH  BC        ;SAVE TEMP RESULT
0290   D2 95 02        3880         JP    NC,SKIPD
0293   09              3885         ADD   HL,BC     ;ADD DIVISOR BACK
0294   E3              3890         EX    (SP),HL   ;REPLACE TEMP RESULT
0295   21 05 0C        3895 SKIPD:  LD    HL,BNUM   ;RESTORE HL
0298   3F              3900         CCF             ;COMPLEMENT CARRY
0299   C3 77 02        3905         JP    LOOPD     ;REPEAT
```

```
029C                 3915 ;*************************************************
029C                 3920 ;                                                 ;
029C                 3925 ; CAL:                                            ;
029C                 3930 ;        EXERCISES ALL SUBROUTINES USED IN        ;
029C                 3935 ;        CALCULATING HR. OR TEMPS.                ;
029C                 3940 ;        OUTPUTS RESULTS TO FRONT PANEL           ;
029C                 3945 ;                                                 ;
029C                 3950 ;*************************************************
029C                 3955 ;
029C  3E 01          3960 CAL:      LD    A,ONE       ;SET UP FLAG
029E  32 00 0C       3965           LD    (FLAG),A    ;FOR HR MODE
02A1  32 09 0C       3970           LD    (LOGCNT),A;SET UP HR ROUTINES
02A4  78             3975           LD    A,B
02A5  E6 02          3980           AND   TWO         ;TEST CAL FLG
02A7  CA BF 02       3985           JP    Z,HICAL     ;IF LOW CAL,CONTINUE
02AA                 3990 ;
02AA  AF             3995 LOCAL:    XOR   A
02AB  32 02 0C       4000           LD    (TIME),A
02AE  3E FF          4005           LD    A,INF       ;LARGE INT. BET R WAVES
02B0  3A 03 0C       4010           LD    A,(TIME+1);STORE IT
02B3  CD D2 02       4015           CALL  GOCAL
02B6  11 F3 02       4020           LD    DE,TABLE    ;CAL TABLE
02B9  CD DE 02       4025 ENDCAL:   CALL  PCAL        ;GET DATA OUT
02BC  C3 00 00       4030           JP    RSTRT       ;RE-START PROGRAM
02BF                 4035 ;
02BF  3E 58          4040 HICAL:    LD    A,CALTL     ;CAL TIME LOW ORDER TO
02C1  32 02 0C       4045           LD    (TIME),A    ;SET TIME=680 MSEC
02C4  3E 02          4050           LD    A,CALTH     ;CAL TIME HIGH ORDER
02C6  32 03 0C       4055           LD    (TIME+1),A
02C9  CD D2 02       4060           CALL  GOCAL
02CC  11 FB 02       4065           LD    DE,HTABLE ;HIGH CAL TABLE
02CF  C3 B9 02       4070           JP    ENDCAL
02D2                 4075 ;
02D2  CD AA 00       4080 GOCAL:    CALL  CALOUT      ;ECG OUT
02D5  AF             4085           XOR   A           ;GET TEMP READY
02D6  32 09 0C       4090           LD    (ECOUNT),A
02D9  3E 0A          4095           LD    A,FIVEDP    ;GET #T CYCLE #
02DB  32 06 0C       4100           LD    (CTRTEM),A;STORE IT
02DE                 4105 ;
02DE  21 0A 0C       4110 PCAL:     LD    HL,TEMPST
02E1  AF             4115           XOR   A
02E2  06 08          4120           LD    B,EIGHT     ;GET TABLE COUNT
02E4  1A             4125 PCONT:    LD    A,(DE)
02E5  77             4130           LD    (HL),A      ;TABLE TO RAM
02E6  05             4135           DEC   B
02E7  CA EF 02       4140           JP    Z,PEND      ;CONTINUE IF NOT DONE.
02EA  13             4145           INC   DE
02EB  23             4150           INC   HL          ;UPDATE POINTERS
02EC  C3 E4 02       4155           JP    PCONT
02EF  CD AA 00       4160 PEND:     CALL  CALOUT      ;RET TO NORMAL
02F2  C9             4165           RET
```

```
02F3                    4175 ;        ***************************************
02F3                    4180 ;        *                                     *
02F3                    4185 ;        *      CALIBRATION TIME TABLES:       *
02F3                    4190 ;        *                                     *
02F3                    4195 ;        *      NOTE: USED BY CAL ROUTINE      *
02F3                    4200 ;        *                                     *
02F3                    4205 ;        ***************************************
02F3                    4210 ;
02F3                    4215 ;CAL INTERVAL FOR T0,T1,T2 AND T50(REF)
02F3                    4220 ;EXPRESSED IN MILLISECONDS
02F3                    4225 ;
        02F3            4230 TABLE:   EQU    $
02F3    1E 01           4235 T0L:     DW     286
02F5    5A 01           4240 T1L:     DW     346
02F7    5A 01           4245 T2L      DW     346
02F9    96 01           4250 T50L:    DW     406
02FB                    4255 ;
02FB                    4260 ;
        02FB            4265 HTABLE:  EQU    $
02FB    1E 01           4270 T0H:     DW     286
02FD    96 01           4275 T1H:     DW     406
02FF    96 01           4280 T2H:     DW     406
0301    96 01           4285 T50H:    DW     406
```

```
TEMPERATURE AND HEART RATE BIOTELEMETRY DEMODULATOR

0303                 4295          ORG   0C00H
0C00                 4300 ;*****************************************
0C00                 4305 ;*                                       *
0C00                 4310 ;*            RAM MEMORY                 *
0C00                 4315 ;*                                       *
0C00                 4320 ;*****************************************
0C00                 4325 ;
      0C00           4330 RAM:    EQU   $           ;BEGIN SYS RAM
0C00                 4335 ;
0C00  0001           4340 FLAG:   DEFS  1
0C01  0001           4345 DUMTM:  DEFS  1           ;TEMPORARY TIME
0C02  0001           4350 TIME:   DEFS  1           ;TIME INTERVAL
0C03  0002           4355 DIVTM:  DEFS  2
0C05  0001           4360 BNUM:   DEFS  1
0C06  0001           4365 CTRTEM: DEFS  1
0C07  0001           4370 TEMP:   DEFS  1
0C08  0001           4375 SAVTIM: DEFS  1
0C09  0001           4380 ECGCNT: DEFS  1           ;R WAVE COUNT
0C0A  0008           4385 TEMPST: DEFS  8           ;T CYCLE STORE
0C12                 4390 ;
0C12  0001           4395 BUSY:   DEFS  1
      0013           4400 RAMEND: EQU   $-RAM
0C13                 4405 ;
      1000           4410 ERAM:   EQU   1000H       ; END OF STACK
```

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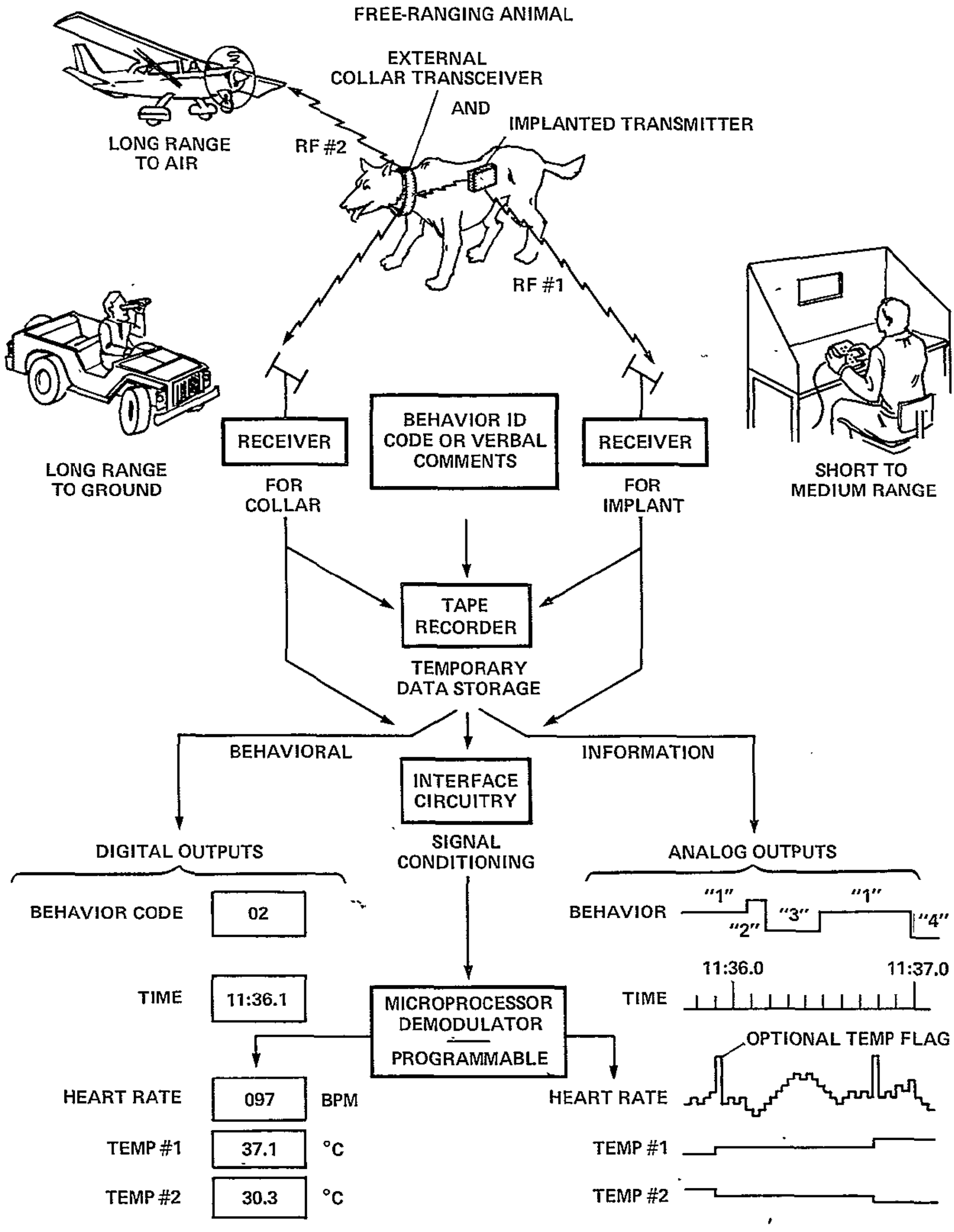


Figure 1.- Telemetry data-acquisition system for heart rate and multiple body temperatures.

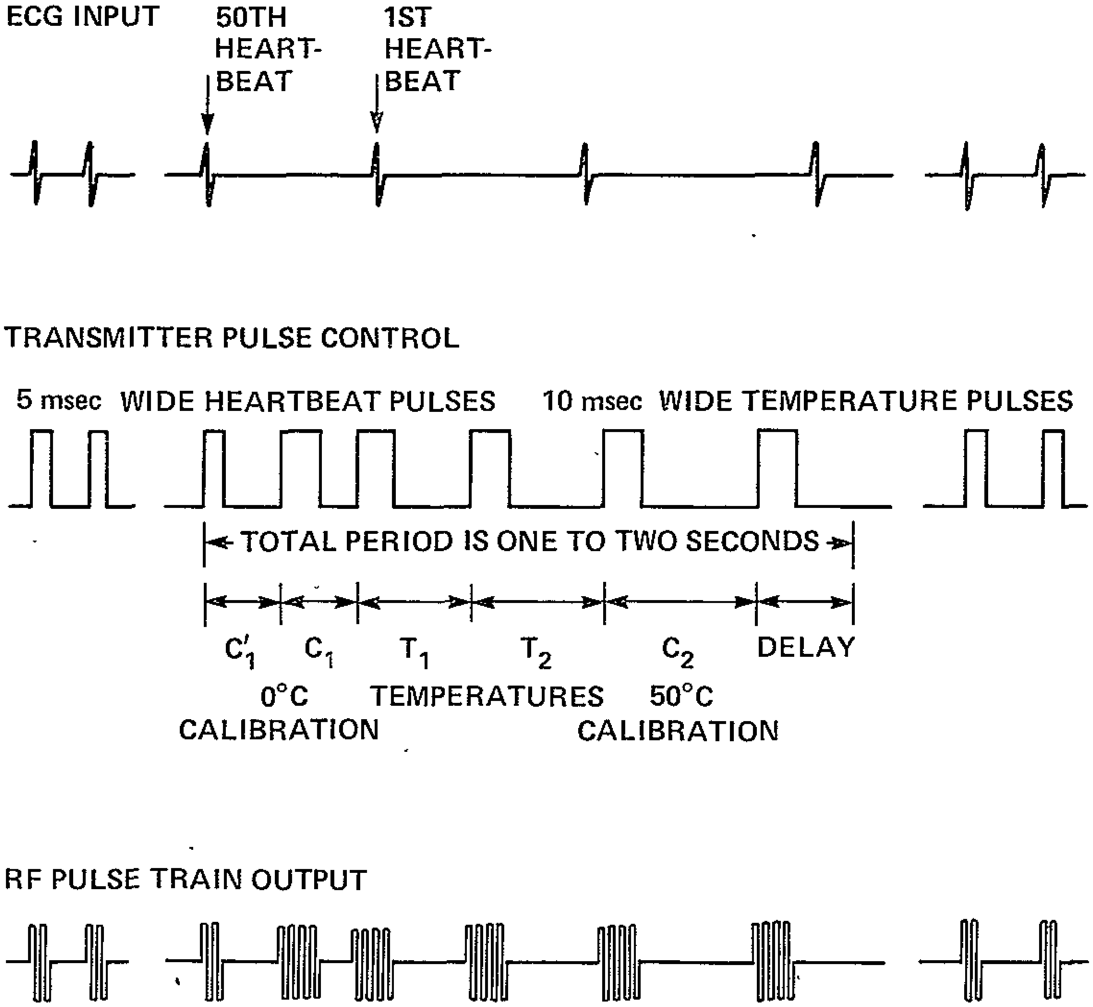


Figure 2.- Modulation scheme for heart rate and multiple body temperatures.

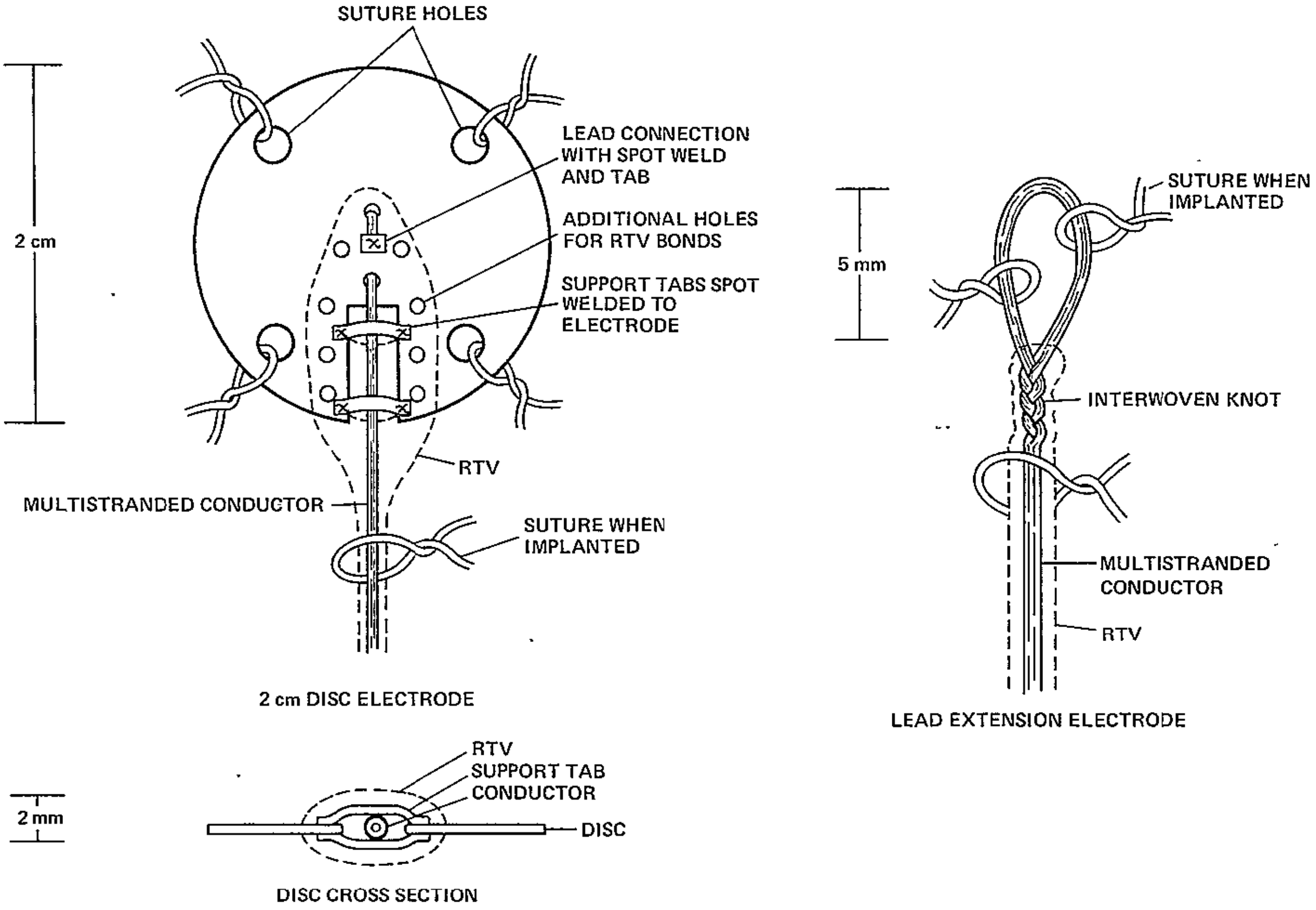


Figure 3.- Implantable ECG electrodes.

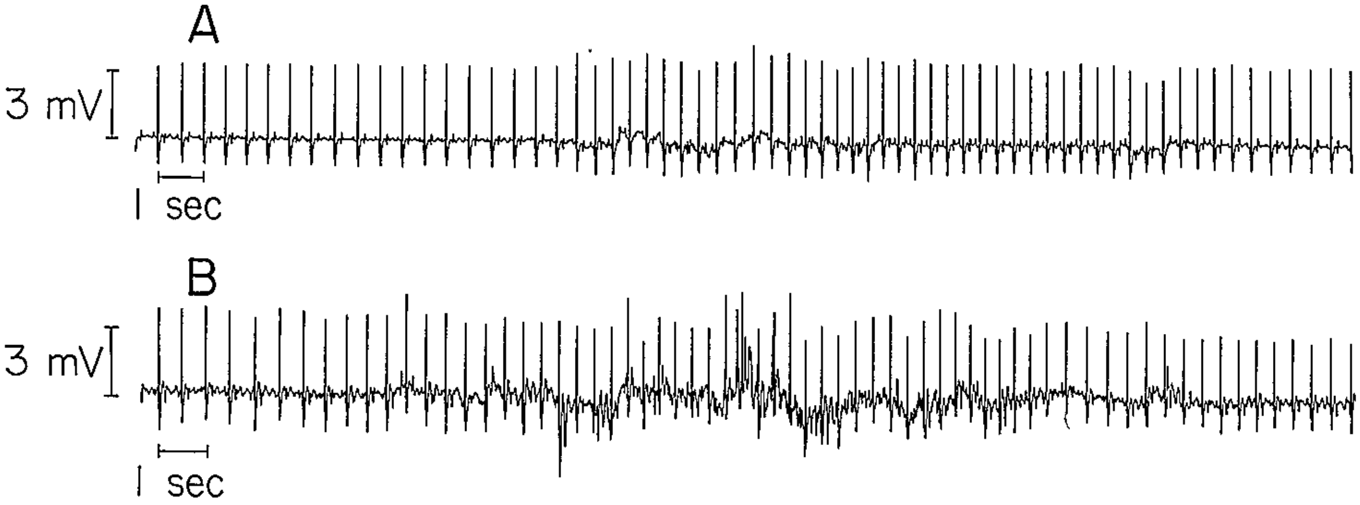


Figure 4.- Activity ECG records from different electrodes implanted in a dog.

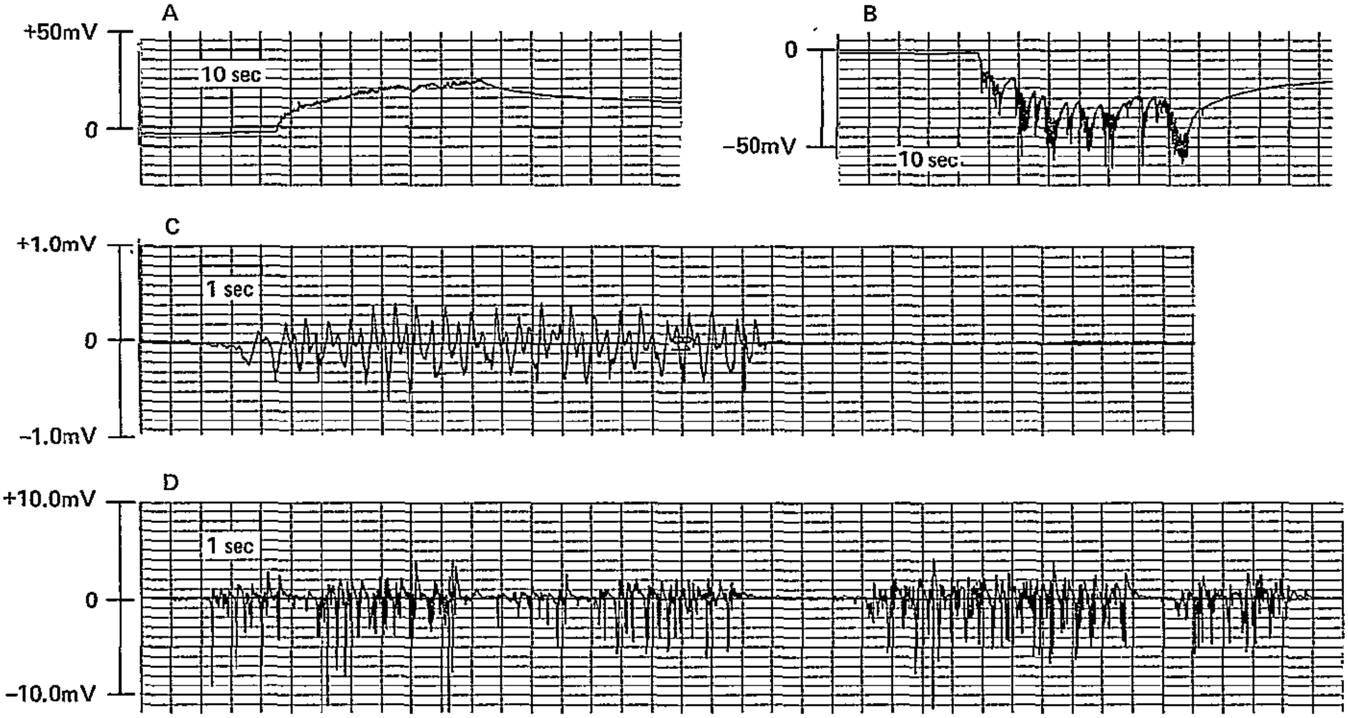


Figure 5.- Disturbance artifact susceptibility of different electrodes *in vitro*.

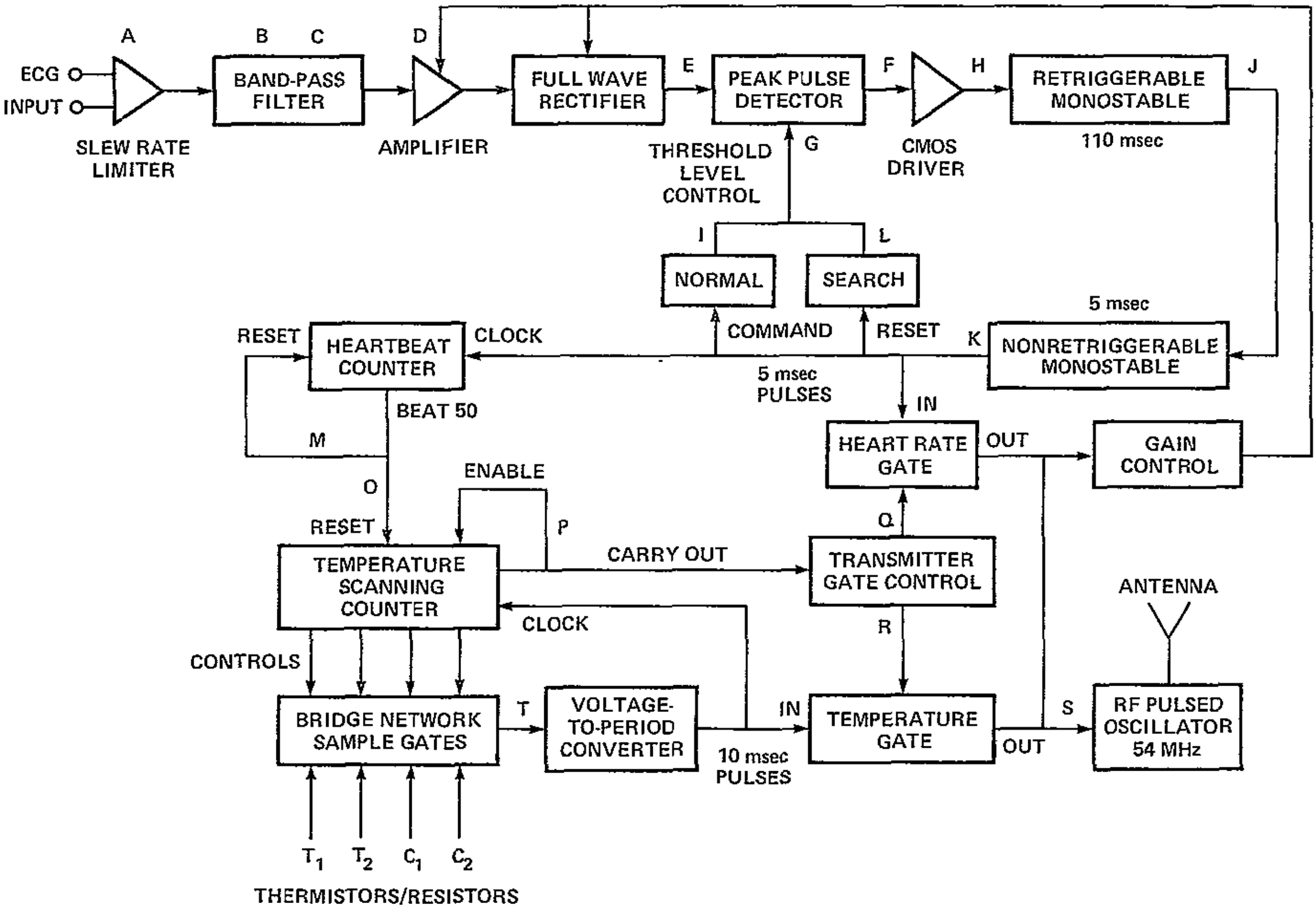
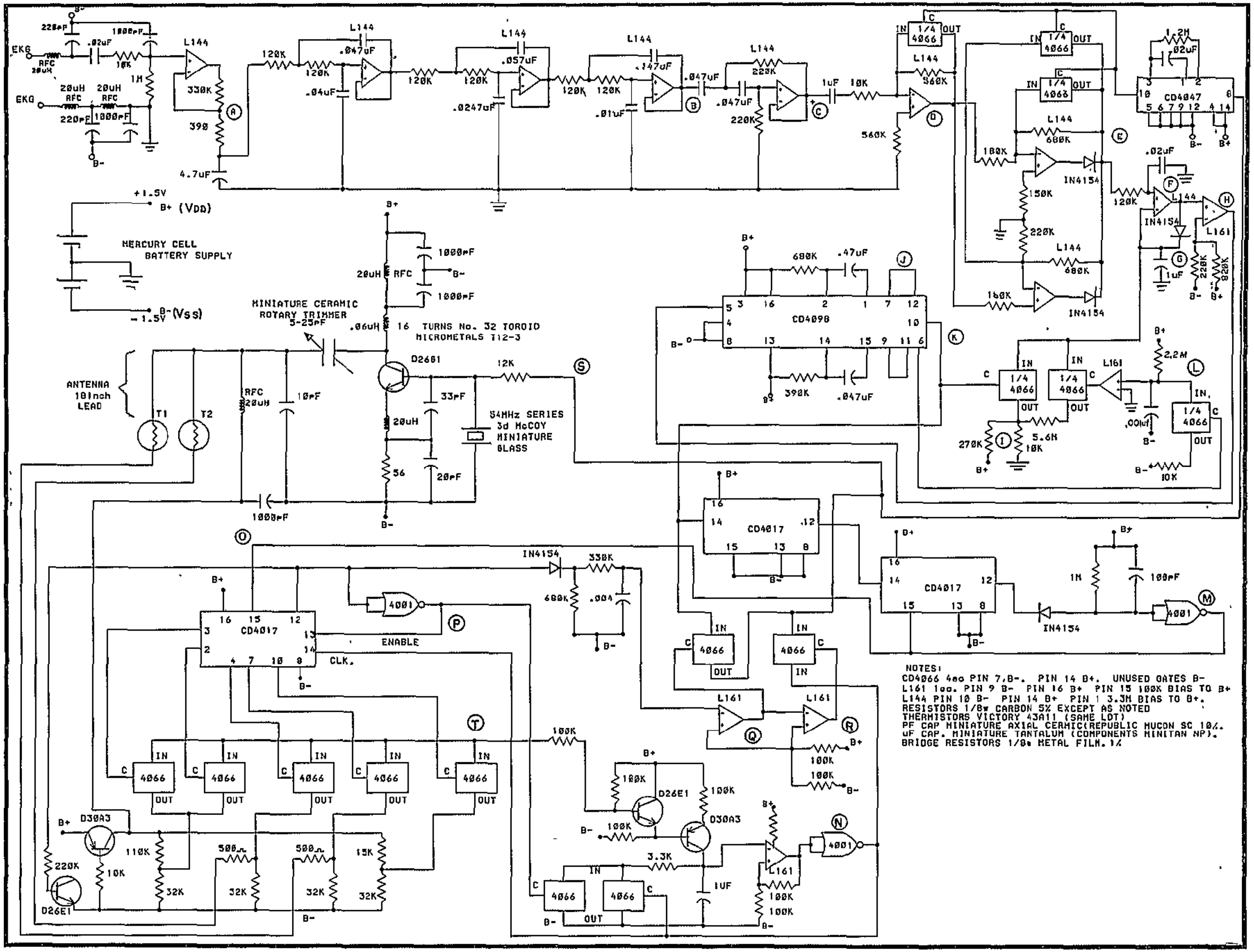


Figure 6.- Block diagram of implantable transmitter.



NOTES:
CD4066 4ea PIN 7,B-. PIN 14 B+. UNUSED GATES B-
L161 1ea. PIN 9 B- PIN 16 B+ PIN 15 100K BIAS TO B+
L144 PIN 10 B- PIN 14 B+ PIN 1 3.3M BIAS TO B+.
RESISTORS 1/8w CARBON 5% EXCEPT AS NOTED
THERMISTORS VICTORY 43A11 (SAME LOT)
PF CAP MINIATURE AXIAL CERMIC(REPUBLIC MUCON SC 10%.
uF CAP. MINIATURE TANTALUM (COMPONENTS MINITAN NP).
BRIDGE RESISTORS 1/8w METAL FILM. 1%

A

Figure 7.- Circuit diagram of implantable transmitter.

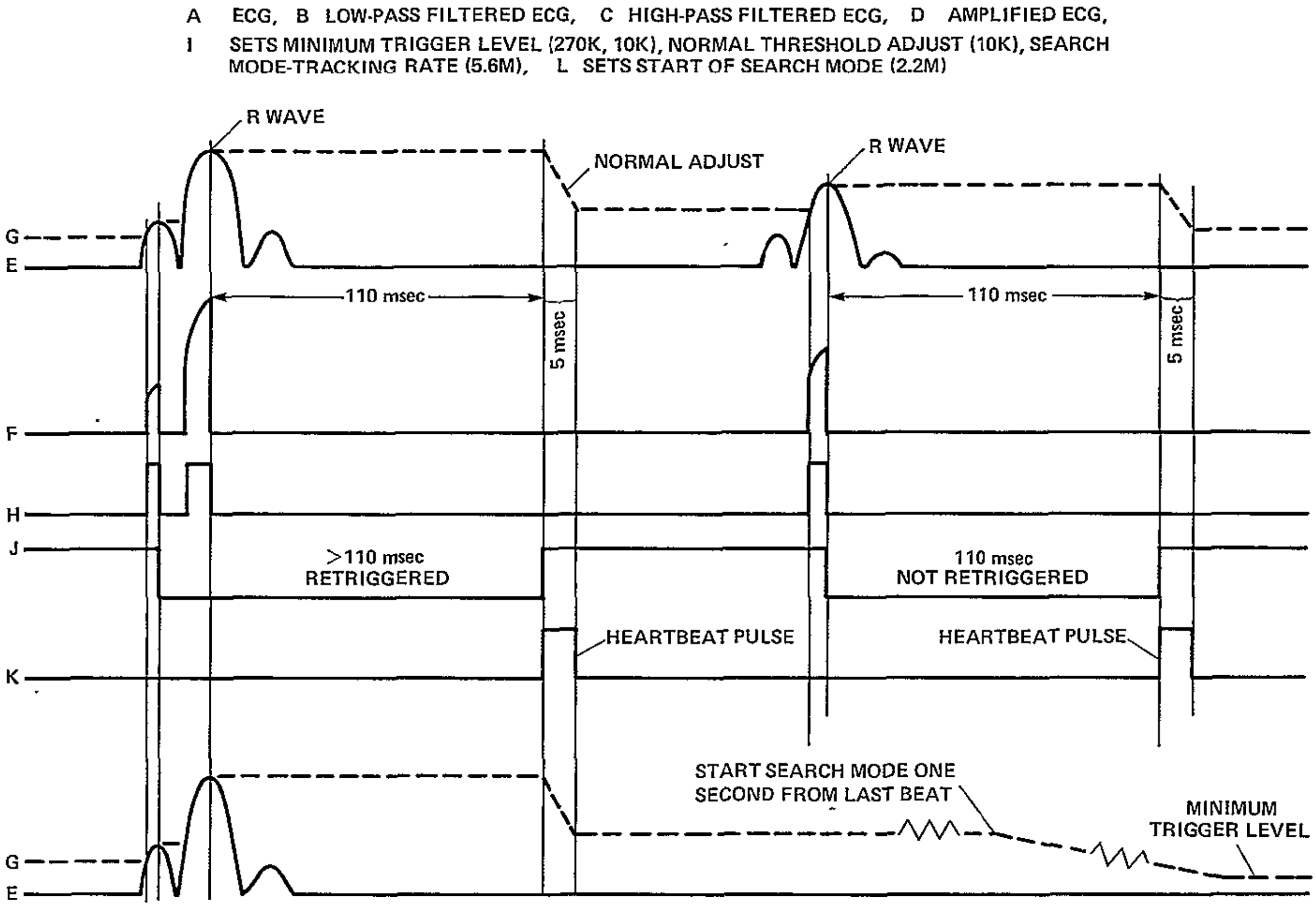


Figure 8.- R-wave detector stage functions for threshold control.

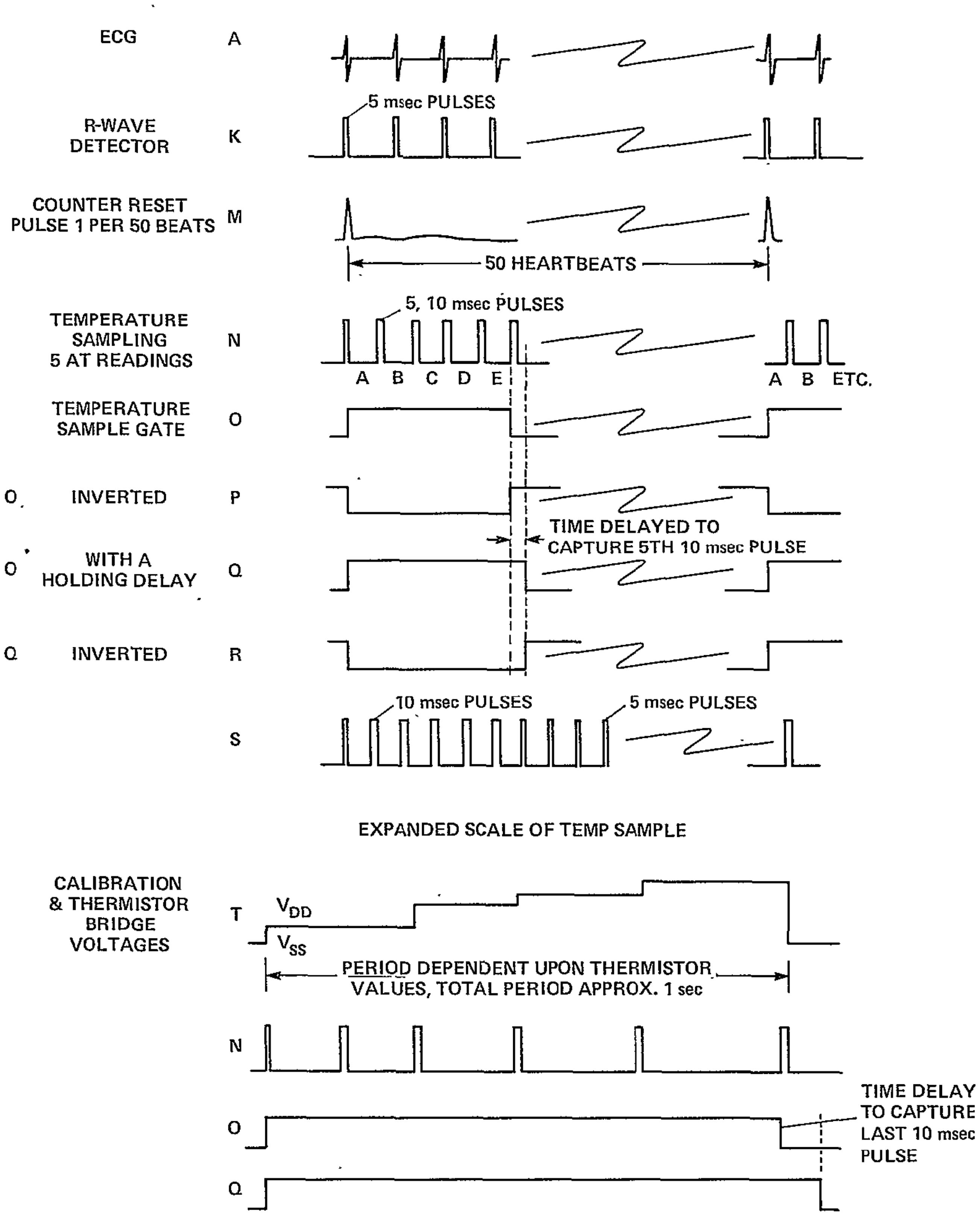
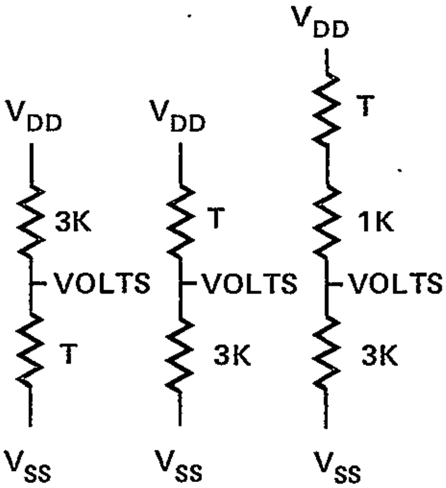


Figure 9.- Temperature waveforms for circuit modulation.



| TEMP., °C | THERMISTOR, kohm | | | |
|---|---|---|---|---|
| 0 | 10 | 2.308 | 0.692 | 0.643 |
| 12 | 5 | 1.875 | 1.125 | 1.000 |
| 25 | 3 | 1.500 | 1.500 | 1.286 |
| 37 | 1.8 | 1.125 | 1.875 | 1.552 |
| 50 | 1.08 | 0.794 | 2.205 | 1.772 |
| | A | B | C | D |

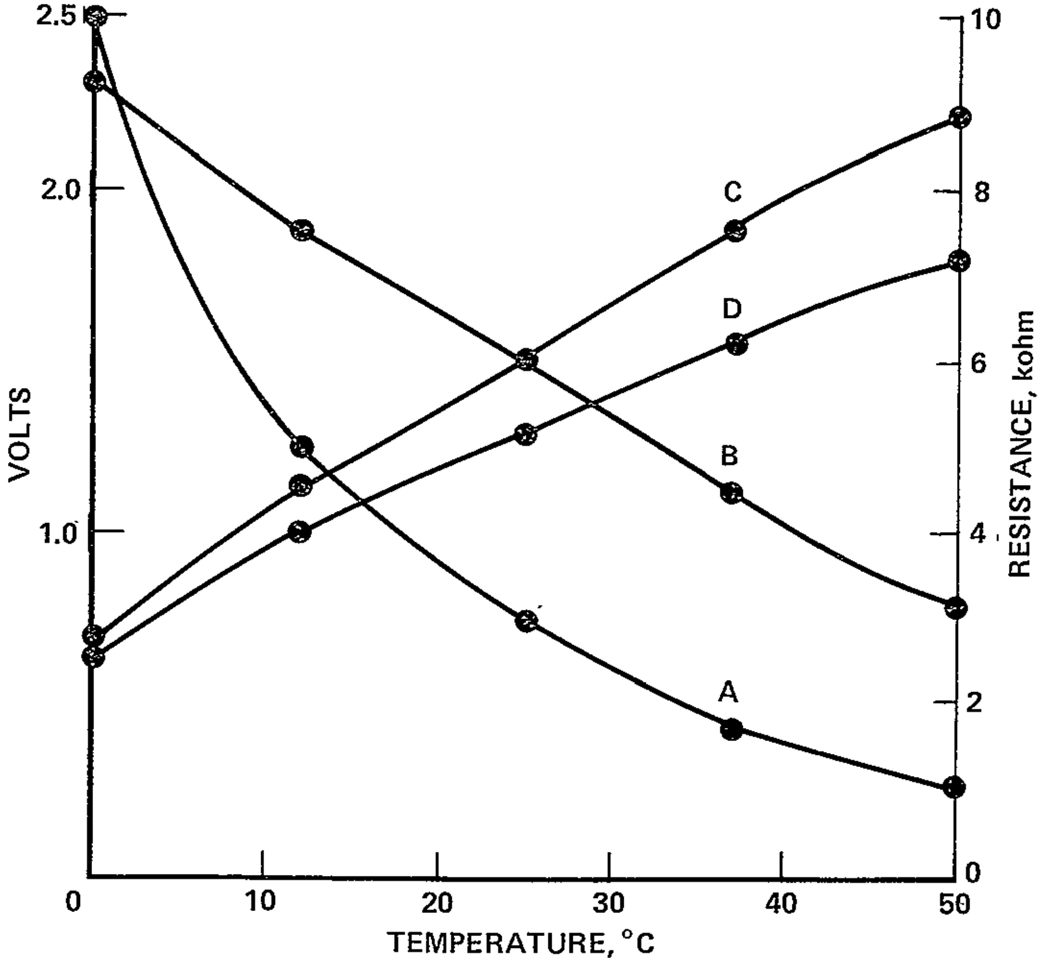
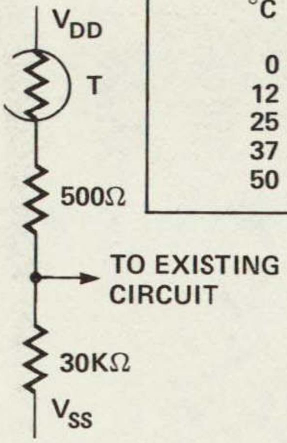


Figure 10.- Thermistor bridge outputs.



| TEMPERATURE °C | THERMISTOR R + 500Ω | OSCILLATOR PERIOD ms 0.5μF ○ | 1μF CAP. ● |
|---|---|---|---|
| 0 | 100.5K | 65.13 | 137.3 |
| 12 | 50.5K | 76.25 | 159.9 |
| 25 | 30.5K | 90.32 | 188.2 |
| 37 | 18.5K | 111.9 | 230.8 |
| 50 | 11.3K | 141.8 | 287.7 |

±0.2 msec ACCURACY FOR ±0.1°C OUTPUT AT LOWER TEMPERATURE RANGE

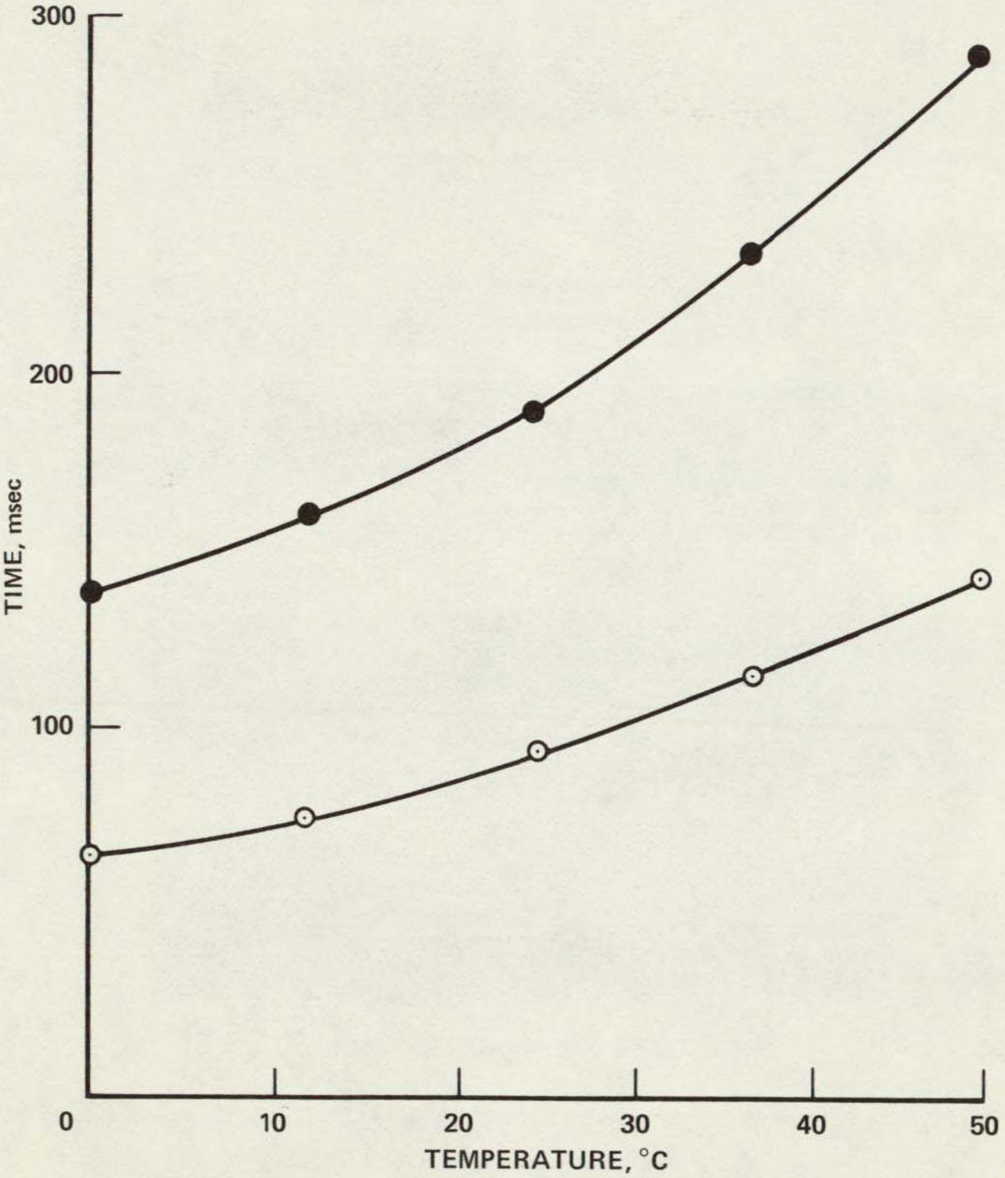


Figure 11.- Thermistor bridge calibrations.

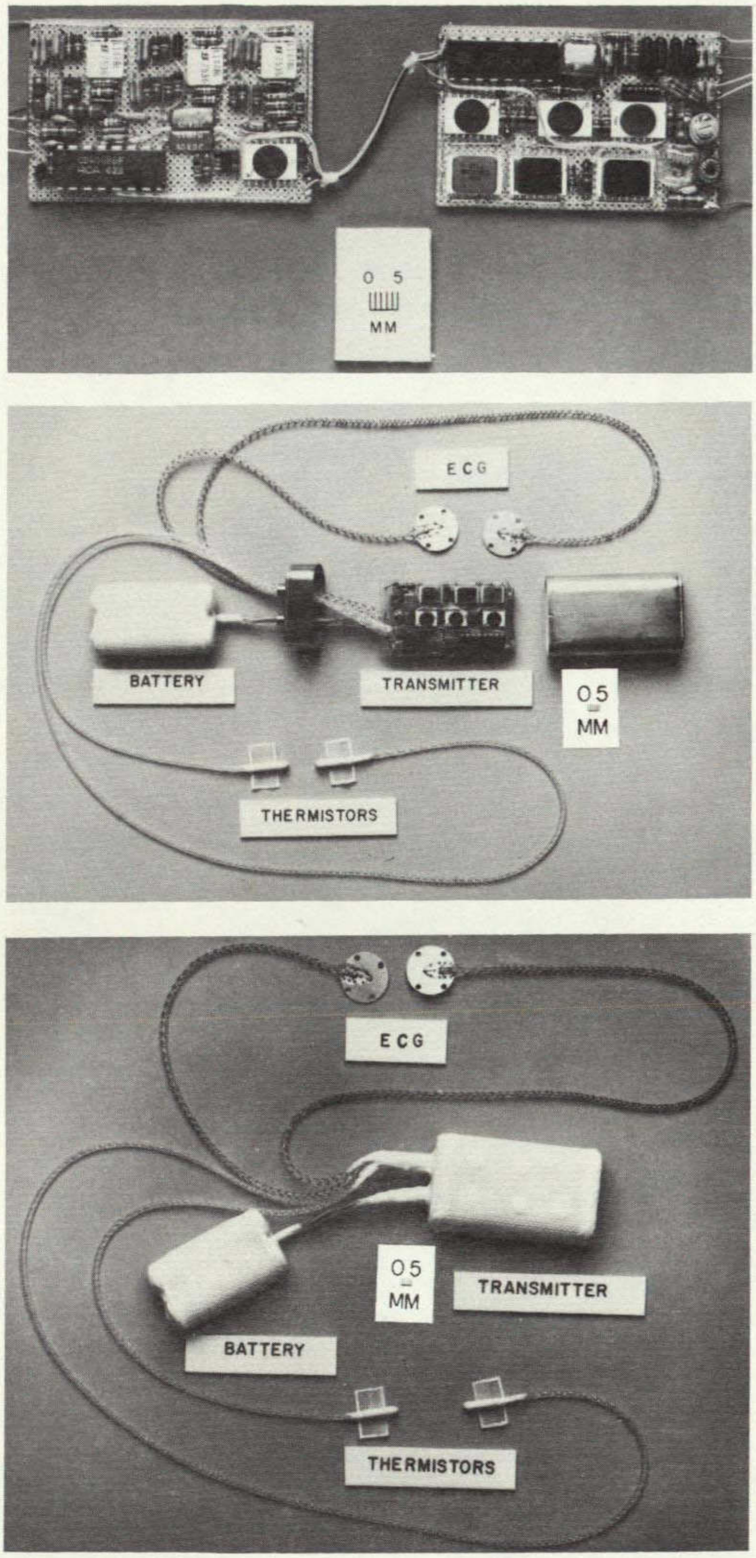


Figure 12.- Transmitter at various stages of prototype packaging.

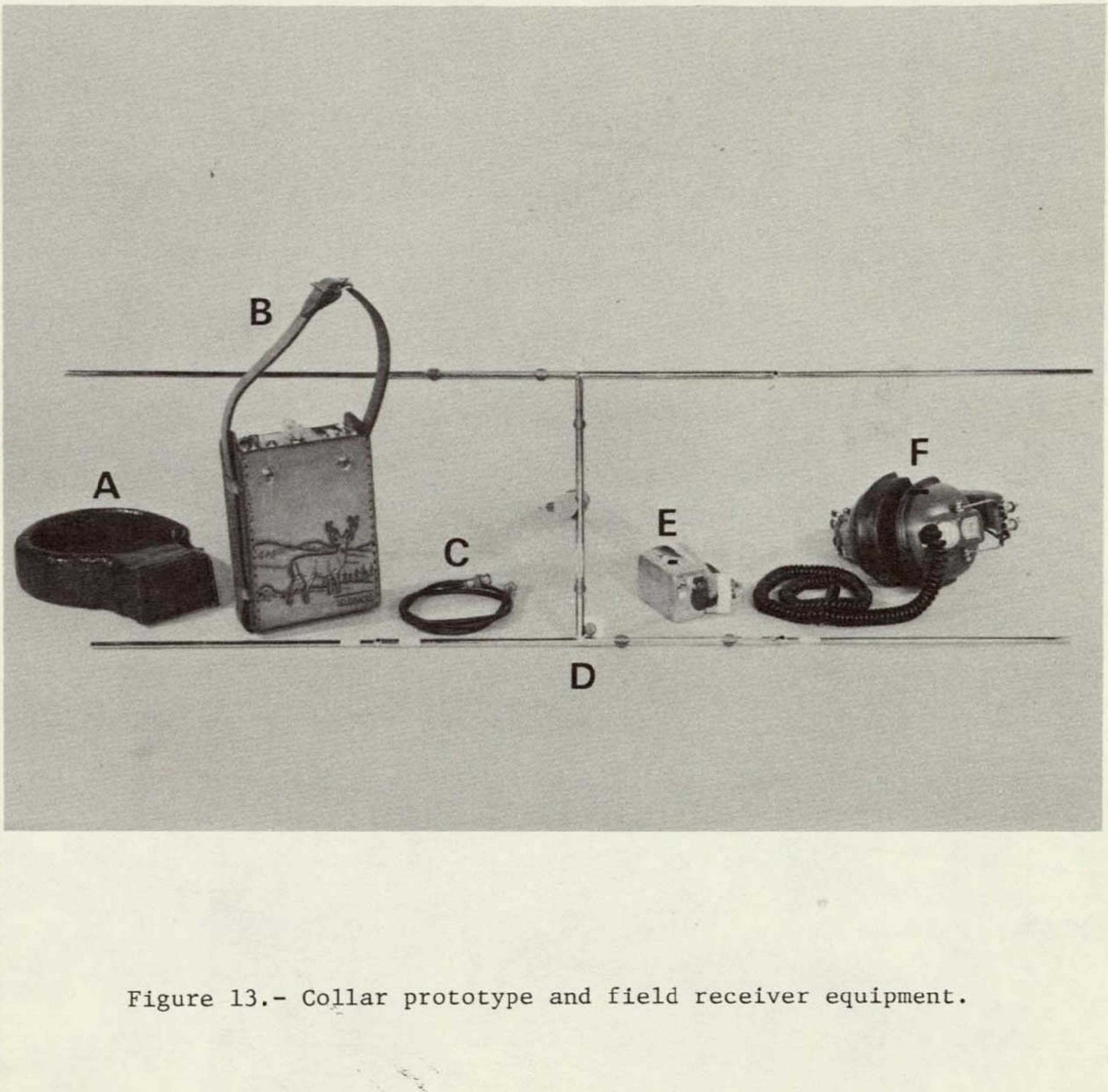


Figure 13.- Collar prototype and field receiver equipment.

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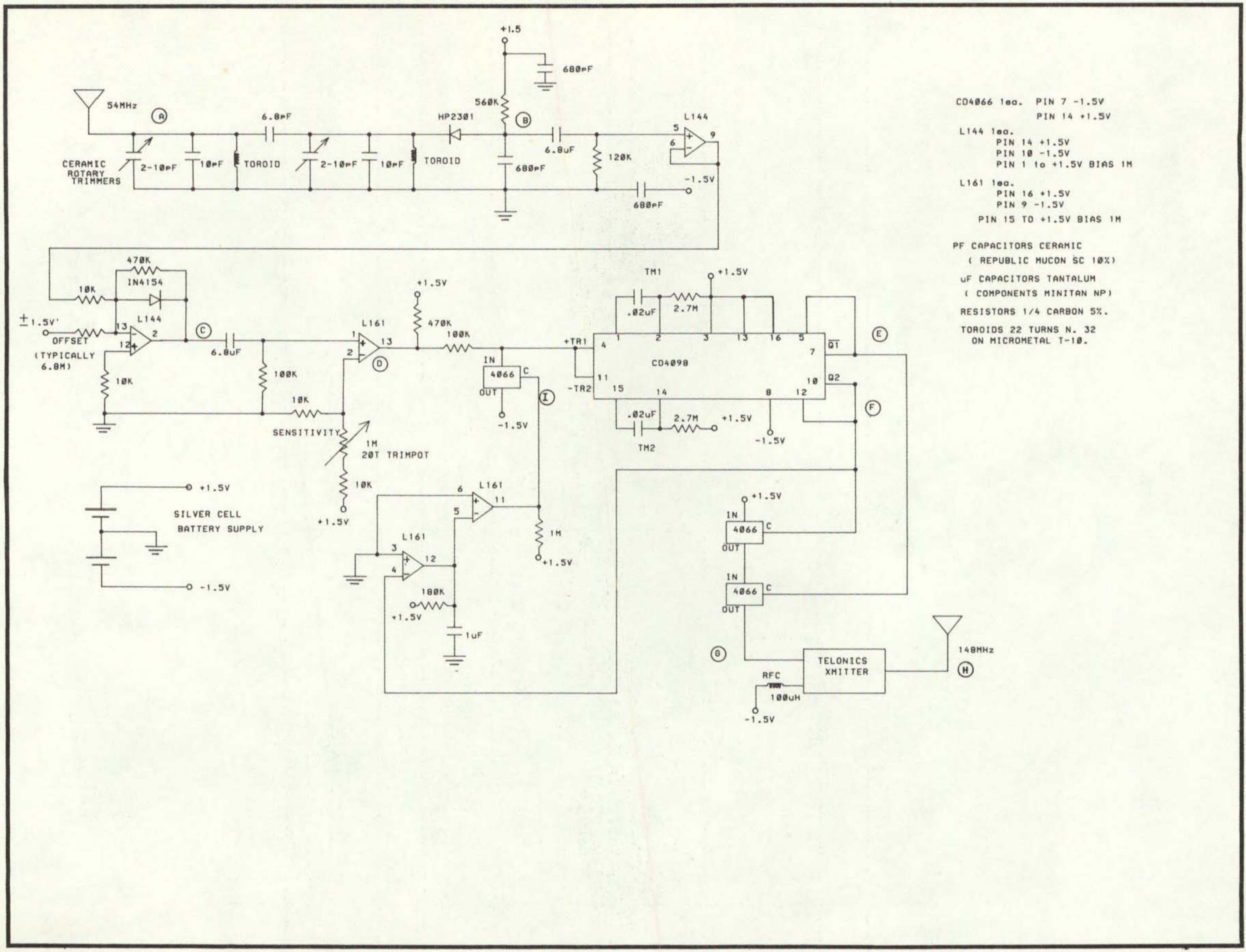


A

Figure 14.- Collar transceiver circuit diagram.

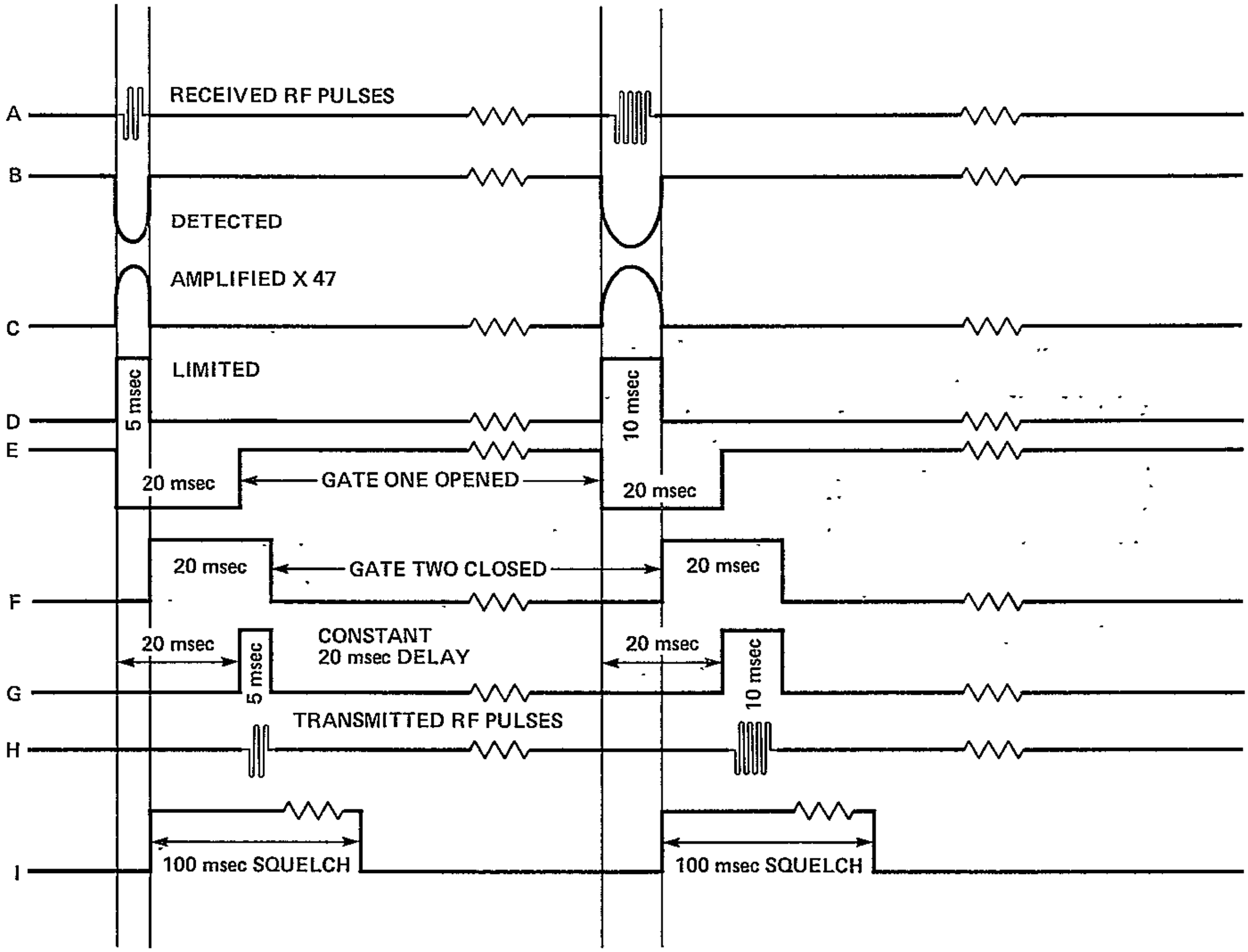


Figure 15.- Collar transceiver timing diagram.

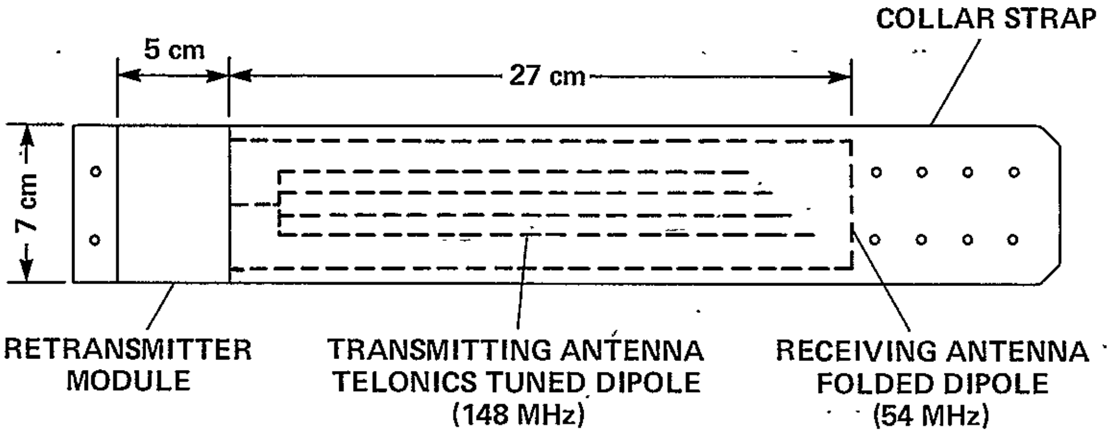


Figure 16.- Collar antenna arrangement.

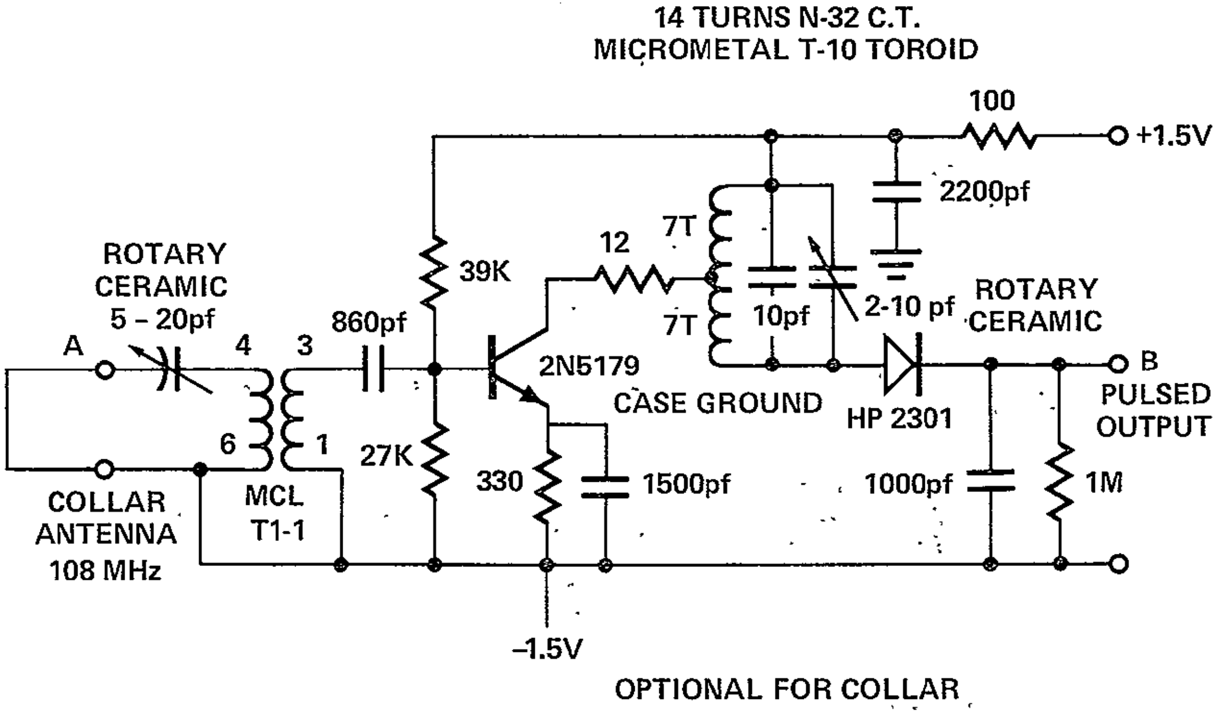


Figure 17.- Circuit diagram for active gain stage.

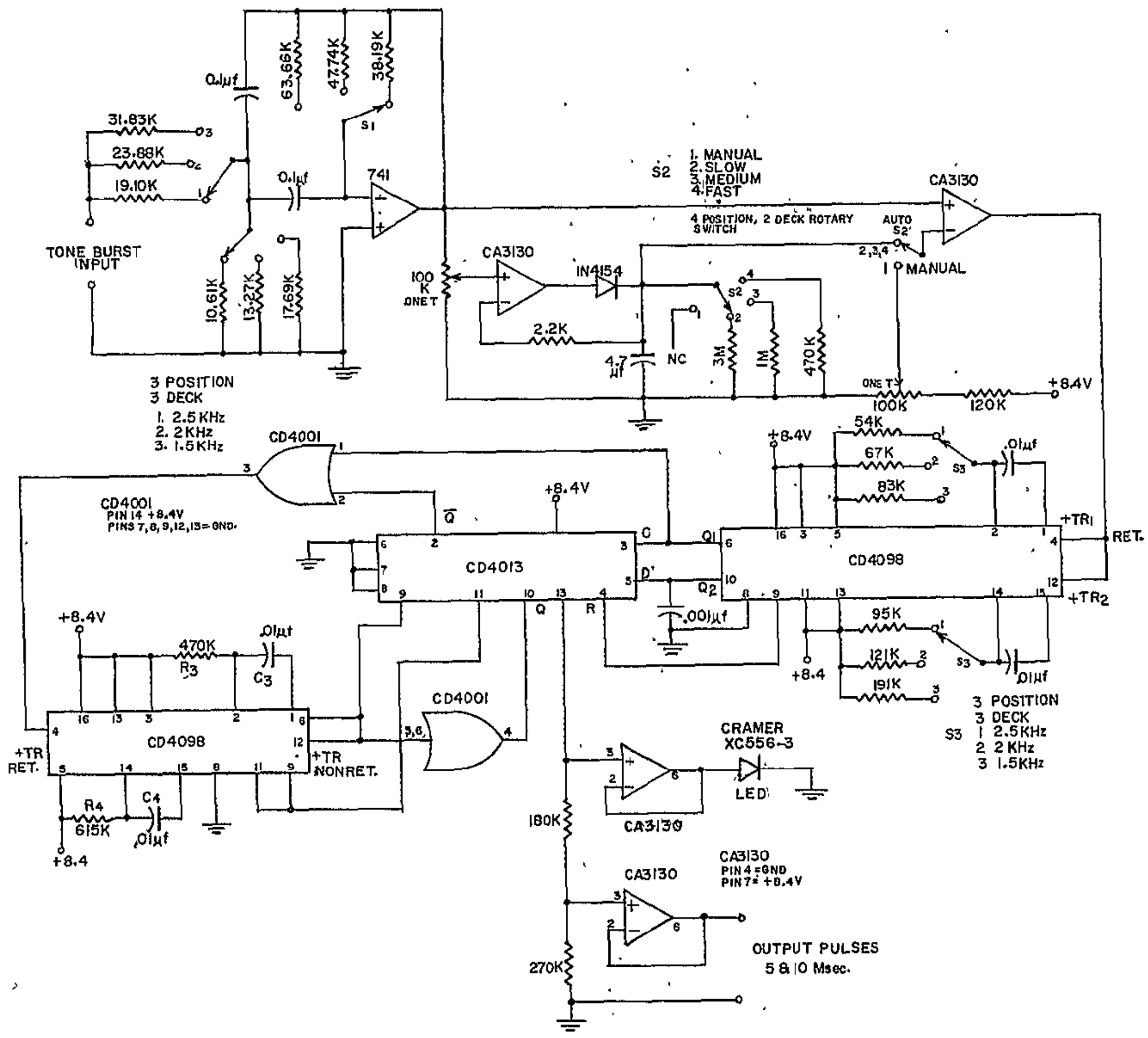


Figure 18.- Interface circuit diagram.

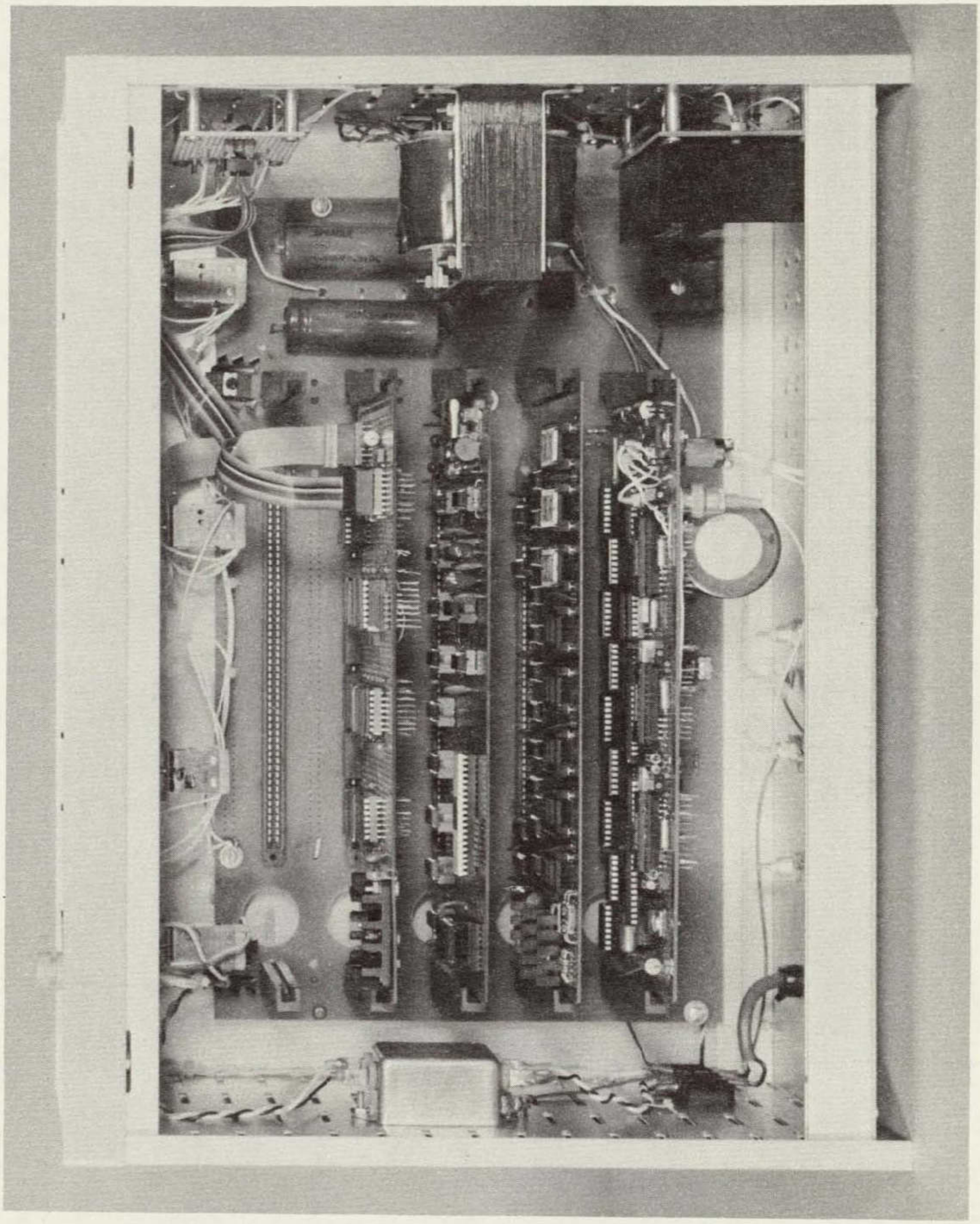
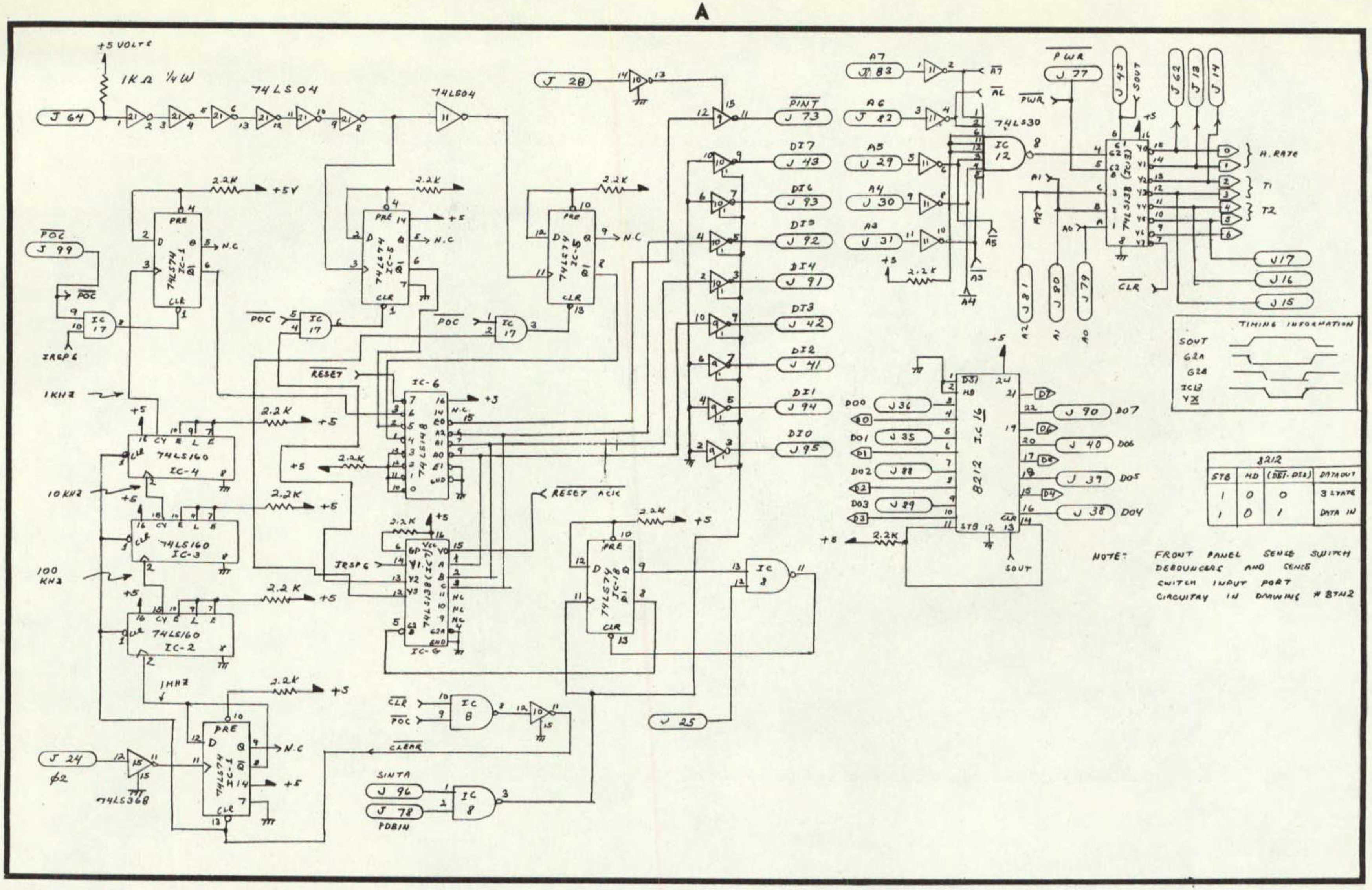


Figure 19.- Top view of demodulator.



| 8212 | | | |
|---|---|---|---|
| STB | MD | (DS1·DS2) | DATA OUT |
| 1 | 0 | 0 | 3 STATE |
| 1 | 0 | 1 | DATA IN |

NOTE: FRONT PANEL SENSE SWITCH DEBOUNCERS AND SENSE SWITCH INPUT PORT CIRCUITRY IN DRAWING #8TN2

Figure 20.- Circuit diagram of demodulator.

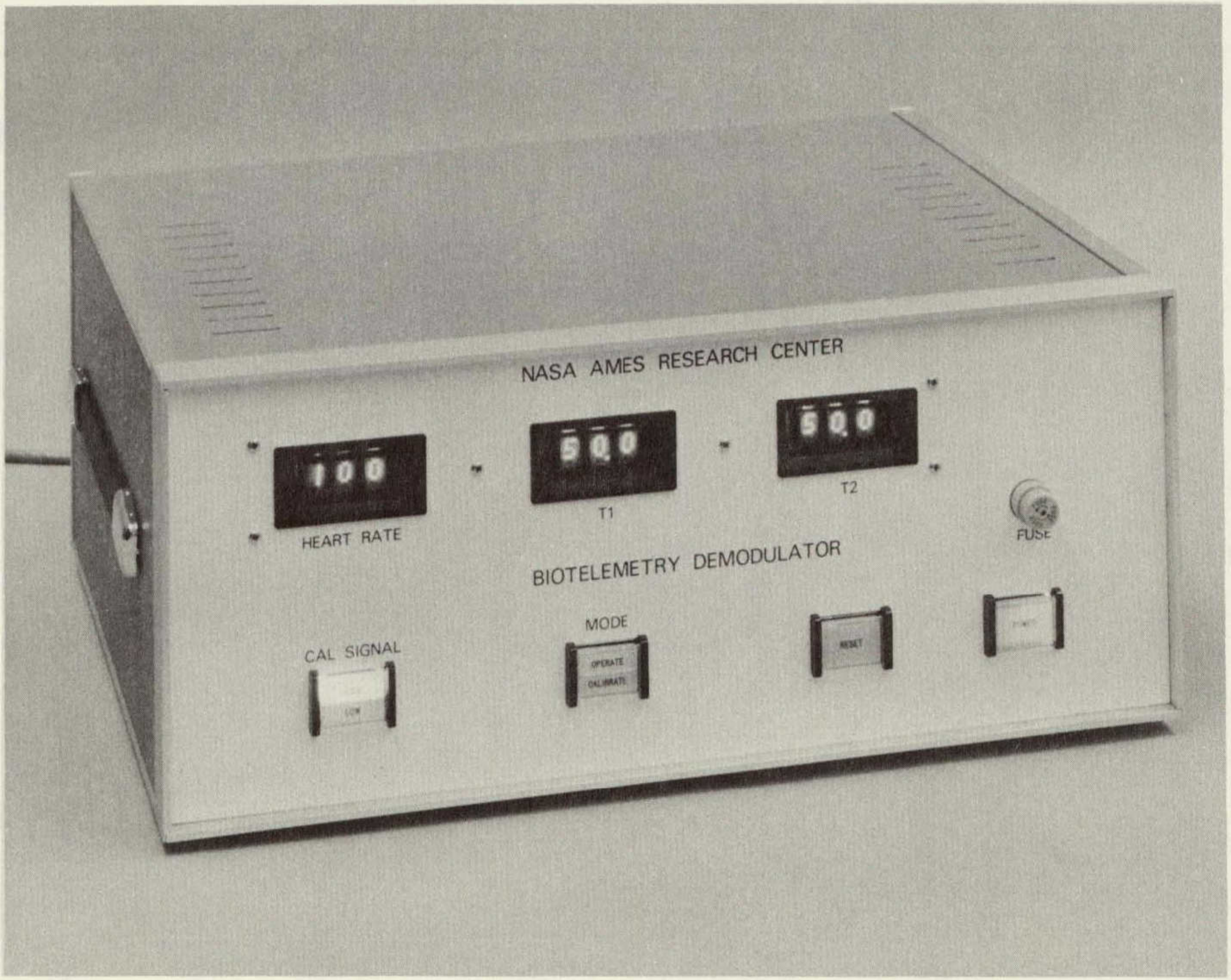


Figure 21.- Front panel of demodulator.

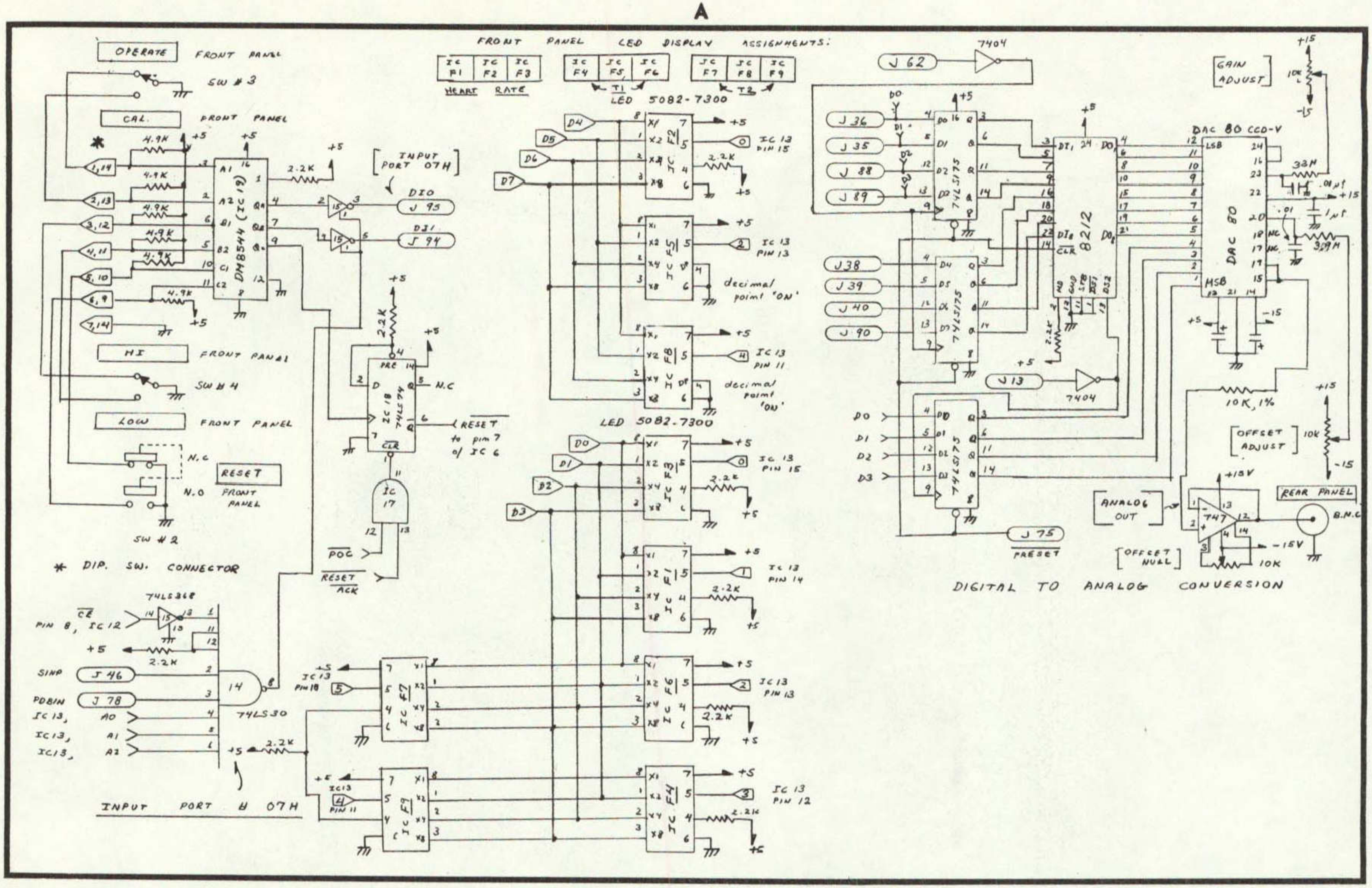


Figure 22.- Continued circuit diagrams of the demodulator.

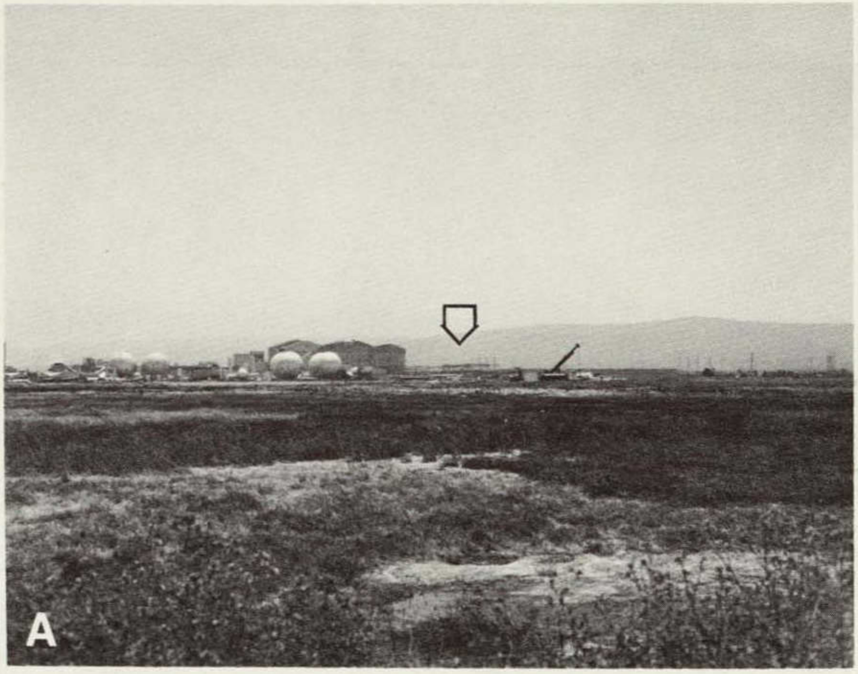


Figure 23.- Views of field test station.

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| 1. Report No.<br>NASA TM-78590 | 2. Government Accession No. | 3. Recipient's Catalog No. |

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|---|---|
| 4. Title and Subtitle<br>A LONG-RANGE AND LONG-LIFE TELEMETRY DATA-ACQUISITION SYSTEM FOR HEART RATE AND MULTIPLE BODY TEMPERATURES FROM FREE-RANGING ANIMALS | 5. Report Date<br>6. Performing Organization Code |
| 7. Author(s)<br>Gordon F. Lund,* Richard M. Westbrook, Thomas B. Fryer, and Rafael F. Miranda | 8. Performing Organization Report No.<br>A-7824 |
| 9 Performing Organization Name and Address<br>NASA Ames Research Center<br>Moffett Field, Calif. 94035 | 10. Work Unit No.<br>199-71-02<br>11. Contract or Grant No.<br>NSG 2293 |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Washington, D.C. 20546 | 13. Type of Report and Period Covered<br>Technical Memorandum<br>14. Sponsoring Agency Code |

15. Supplementary Notes

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16. Abstract

A long-range and long-life telemetry system for heart rate and multiple body temperatures from free-ranging animals has been designed. This system includes an implantable transmitter, external receiver-retransmitter collar, and a microprocessor-controlled demodulator. The size of the implant is suitable for animals with body weights of a few kilograms or more; further size reduction of the implant is possible. The ECG is sensed by electrodes designed for internal telemetry and to reduce movement artifacts. The R-wave characteristics are then specifically selected to trigger a short radio frequency (RF) pulse. Temperatures are sensed at desired locations by thermistors and then, based on a heartbeat counter, transmitted intermittently via pulse interval modulation. This modulation scheme includes first and last calibration intervals for a reference by ratios with the temperature intervals to achieve good accuracy even over long periods. Pulse duration and pulse sequencing are used to discriminate between heart rate and temperature pulses as well as RF interference. The implanted transmitter might be used alone for experiments on animals that frequent particular locations within a large territory; on animals in virtually any laboratory situation; or on animals in moderate-sized enclosures, such as those in a zoological garden. The implanted transmitter is otherwise interfaced with the receiver-retransmitter collar that employs commercial tracking equipment to achieve the long-range transmission. Peak energy is consumed only during the short RF pulses so that average current drain of either transmitter is in the range of tenths of milliamperes. The RF pulses from either transmitter are processed by the microprocessor controlled demodulator for the characteristics of pulse durations, intervals, and sequence. The output provides analog beat-to-beat heart rate and periodically updated temperatures as well as digital display. Heart rates to several hundred beats per minute (BPM) and body temperatures within a range of zero to 50° C with 0.1° C in resolution of change or better seem feasible. The objective of the design was to achieve a high degree of experimental flexibility and overall high quality in performance. The system was tested in prototype form on a dog.

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|---|---|
| 17. Key Words (Suggested by Author(s))<br>Long-range telemetry<br>Radio telemetry<br>Heart rate<br>Temperatures<br>Data acquisition | 18. Distribution Statement<br>Unlimited<br>STAR Category - 51 |

| | | | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of Pages<br>73 | 22. Price*<br>$4.50 |

*For sale by the National Technical Information Service, Springfield, Virginia 22161