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A MINIATURIZED DIGITAL TELEMETRY SYSTEM FOR
PHYSIOLOGICAL DATA TRANSMISSION



NASA Contract NAS 9-11162

March 31, 1978

William M. Portnoy, Principal Investigator

Larry J. Stotts, Research Assistant

Biomedical Systems Laboratory
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CHAPTER I

INTRODUCTION

A. General.

Telemetry is the transmission of data over a communication link to a remote location; physiological telemetry, in particular, involves the transmission of such data as EEG, ECG, respiration, heart rate, temperature, and similar physiological variables. Since 1949, a great number of physiological radio telemetry systems have been developed,^{1,2,3} ranging from large complex multi-channel, multi-patient monitoring systems for hospital use,⁴ through battery-powered multichannel portable units for exercise physiology,^{5,6,7} to small single-channel implantable systems for biological experimentation. The development of physiological monitoring in space has introduced special constraints, including substantial reduction in size of a unit, and at the same time, increased information handling capability. The specific requirement for a practical, miniature telemetry system, capable of transmitting digitally encoded physiological information, is the basis for this work.

B. Purpose and Scope of the Work.

The physiological data telemetry system described in this work was designed under contract to the NASA Lyndon

B. Johnson Space Center, following a request from NASA to design and fabricate a system to their specifications; the request was based on the failure of previous designs to meet these specifications. The earliest system was submitted to NASA by a commercial space electronics company; although portable, the system was cumbersome, consisting of a belt arrangement, consumed excessive power, and was based on a 9-bit logic system which was not compatible with any other commercial logic, and which could not be supported by conventional technology. In a second design,⁵ size and power were reduced; however, the second design required the incorporation of an existing encoder. The encoder was originally used with a less sophisticated system than was now required, and its use with the new system resulted in errors in the received data. It was then that the present work was negotiated with NASA. A completely new circuit design was to be provided and implemented, based on performance specifications, and meeting, as far as possible, specific design requirements; however, these could be modified if performance would otherwise be degraded. Inasmuch as two previous attempts had been unsuccessful, and because the state-of-the-art was changing so rapidly, this program represented a considerable challenge. Nevertheless it was agreed to provide a system with low power consumption and small size. The unit was to transmit PCM encoded

data, provide two-way voice communication, and be transponded on and off from ground base station (GBS). Power to all systems in the portable unit was to be controlled exclusively by the GBS, the subject to have only temporary control of a few subsystems. The purpose of removing control of transmission from the subject was to prevent interruption, by the subject, of transmission in crisis situations. (A subsidiary of power control by GBS was the reduction of power consumption in unused subsystems.)

The most accurate telemetry system is one which is independent of the type of radio link employed. By converting input physiological data into a digitally coded word before transmission, nonlinearities which arise during transmission do not affect the quality of the received, decoded data. Such encoding permits the use of any type of transmitter, eliminating the reliance on the linearity required by direct modulated systems. However, if crystal control of frequency is required, the design becomes very complicated; wideband deviation of a crystal oscillator is not easily obtained, and direct frequency modulation requires considerable undesirable circuit complexity. The simplest transmitter design, an amplitude modulated (AM) signal, is frequently noise sensitive. A pulse-coded, two state, phase-shifted modulation scheme⁸ (and digital filtering, if required) permits the use of simple AM cir-

cuitry to obtain the noise performance of FM. The specific objective of this work was to design and build a reliable, small, pulse-code modulated telemetry system which had low power consumption, a two-way voice link, and at least seven physiological data channels. A description of the operation and content of the overall system is provided in Chapter II. The electronic circuit design of the various subsystems is discussed in Chapter III. Chapter IV is a summary of performance of the system, and a discussion of its applications.

CHAPTER II
DESCRIPTION OF THE SYSTEM

A general overview of the system and a description of operation is presented in this chapter. The total system is decomposed into its various subsystems, and each subsystem is described in detail.

A. Specifications.

This work was originally intended to provide an upgraded, miniaturized model of the unit produced previously under NASA contract,⁵ but because of the complexity and excessive power consumption of the original NASA Ames Research Center (NASA/ARC) PCM formatting scheme, as well as the power consumption of the radio links, a complete redesign of the system was required. The original specifications were amended somewhat to be consistent with the redesign, and are presented below:

1. Battery powered, low power consumption;
2. Single crystal controlled transmitter with voice operated switch (VOX) control;
3. Seven data channels plus two way voice channel;
4. Control format designed to inhibit subject termination of system operation;
5. Calibration capability for each data channel;
6. Inputs compatible with insulated electrodes.⁹

These specifications were met in each case, and exceeded in one: thirteen data channels (seven dc and six analog) were provided.

B. Description of the Overall System.

The system consists basically of a portable unit worn by the subject, and a GBS. (A block diagram of the complete system is shown in Figure 1.) The portable unit is composed of a single crystal controlled transmitter with AM transmission of digital data and narrowband FM transmission of voice; a crystal controlled FM receiver; thirteen input channels followed by a PCM encoder (three of these channels are designed for ECG data); a calibration unit; and a transponder control system. The GBS consists of a standard telemetry receiver, a decoder, and an FM transmitter for transmission of voice and transponder signals to the portable unit.

C. Portable Unit.

1. Transponder Control.

In order to assure that the subject cannot terminate any physiological data transmission (short of deliberately divesting himself of the system or portions of it), as well as to conserve power, the base unit controls continuous operation of all subsystems. However, PCM data may be temporarily interrupted, but not terminated, by VOX

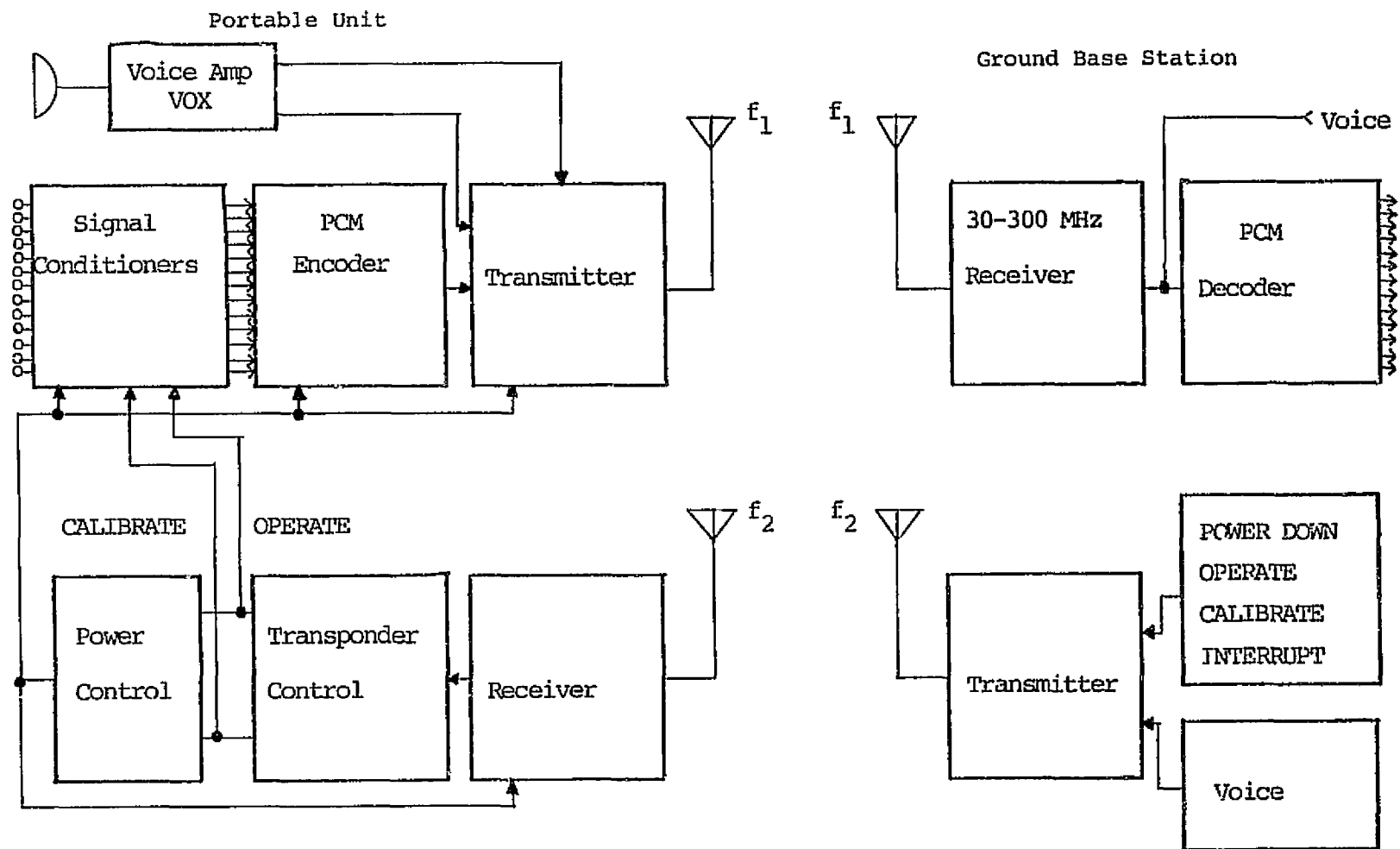


Figure 1. System Block Diagram

control, to permit voice transmission. Transponder control of the portable unit is obtained by transmission of two tones from the base unit, providing four modes of control by GBS combined with VOX control by the subject. These four modes of operation are:

1. CALIBRATE mode. Power to receiver, encoder and transmitter; a 1 mV, 3 Hz square wave calibration signal applied to signal conditioner inputs; enabled temporary VOX interruption of data.

2. OPERATE mode. Power to receiver, encoder, and transmitter; physiological signals (Leads I, II, and III of EKG) fed into signal conditioners; enabled temporary VOX interruption of data.

3. INTERRUPT mode. Power to receiver, no power to transmitter or encoder; voice reception from base unit.

4. POWER DOWN mode. No power to encoder or transmitter; receiver operates in sampling mode; enabled VOX initiation of power to transmitter.

2. Receiver.

The receiver in the portable unit operates in a sampling mode in the Power Down mode, that is, power is switched to the receiver during relatively short periods (500 msec) every 5 seconds, so that it can detect a change in control instructions. If a change is detected, the receiver is locked on and remains on until the control signal from GBS

is terminated. This type of operation results in lower power consumption and increased battery life.

The receiver itself a basic superheterodyne, narrow band FM receiver.¹⁰ The front end (r.f. amplifier, local oscillator, and mixer) converts the incoming 154.57 MHz signal into a 10.7 MHz IF frequency. This signal is amplified, limited, and discriminated, and the resulting audio signal is amplified and applied to the transponder and earphone. These functions are performed by a single integrated circuit chip (Plessey SL665), which is a low power version of a similar RCA device. A low power phase-locked loop (PLL) detector is also available, but was not used for several reasons. First, the PLL receiver cannot operate at 10.7 MHz, so that a down-conversion stage is needed; also, voltage to the PLL receiver requires a high degree of regulation for good operation. (Center frequency drift with voltage of the phase locked loop in the previous design⁵ resulted in sporadic operation of the receiver and inhibited good control.) Either requirement introduces additional circuit complexity and power consumption, and the PLL receiver was discarded as part of the redesign. The redesigned receiver operates over a wide range of voltages, providing a reliable voice and control link.

3. Transmitter.

The transmitter consists of a frequency modulated 90 MHz

crystal oscillator, followed by two Class C power amplifiers, the last being amplitude modulated by the two-state PCM signal. The original NASA requirement that the transmitter be crystal-controlled and frequency modulated at the same time cannot reasonably be satisfied with a miniaturized, low power design when only one transmitter is used to transmit two different signals with widely differing characteristics. Introducing a linear frequency deviation of 5 KHz into a crystal controlled oscillator is relatively simple for voice transmission alone, but a change of 50 KHz in the center frequency for PCM is not easy to obtain in the same circuit. The previous design⁵ employed a pseudo-indirect scheme whereby a combination of frequency and phase modulation was used to try to obtain a linear deviation. The resulting transmitter was quite complex, and produced a distorted PCM signal at the GBS, resulting in a number of data errors. In this work, several possibilities for meeting the requirement of a single crystal-controlled FM transmitter were considered. First, two oscillators 50 KHz apart were alternately switched by the PCM data into an output power amplifier. Voice transmission was obtained by way of direct frequency modulation of one of the oscillators. Switching transients, however, limited the switching rate to below 50 KHz, the lowest rate acceptable for accurate data reception. In a second scheme, the

phase of a crystal oscillator was switched between 0 and 180 degrees by the PCM data applied to a diode switching network, but again switching times and transients limited the switching rate to values below 50 KHz. Narrowband transmission of voice and PCM was also considered. The range for PCM transmission is very short for any reasonable input power level; narrowband transmission was satisfactory only if a distributed antenna system had been available to the GBS receiver, a requirement which it did not seem reasonable to impose.

Finally, noise levels on the AM and FM channels at the transmission frequency were equal at low level gains, and at the short operating range required (100 ft), there was no noise advantage to using FM instead of AM. The PCM signal is a two-state digital signal, composed of only two discrete pulse widths. If high frequency noise ever becomes important during the use of the system, the two digital frequencies present in the PCM data can easily be recovered by digital filtering.

4. PCM Encoder.

There are two general modulation categories: sub-carrier modulation and digital modulation. In the former category, different subcarrier frequencies (either frequency or amplitude modulated, and corresponding to sep-

arate channels) are mixed at a transmitter and separated with filters at a receiver. This technique is not suitable for the present application. First, for any significant number of channels, subcarrier modulation requires a large band-width and is subject to cross-talk. Also, and more importantly, subcarrier modulated signals are not convenient for receiving and retransmitting, a requirement imposed by the onboard repeater transmitter.

Digital modulation techniques, among which are PCM, PPM, Δ - Σ , PWM and PAM, were primarily developed to be used with repeaters; furthermore, depending on the carrier modulation scheme employed, digital techniques exhibit better channel separation (using time division multiplexing) and higher noise immunity, than subcarrier systems. The location techniques (PAM, PPM, PWM) are not as reproducibly accurate as PCM, which, with the appropriate carrier modulation, is by far the most efficient of the digital techniques; Δ - Σ , because of its larger bandwidth, is a close second.^{11,12,13,14} Δ - Σ is basically pulse-rate modulation except that it is synchronized to a clock (Figure 2). (For single-channel operation, however, the synchronization is not mandatory.) This modulation scheme was considered originally, and two modulators were built; it was found that a clock frequency of 4 KHz was necessary to reconstruct accurately a 100 Hz signal. It follows that an eight chan-

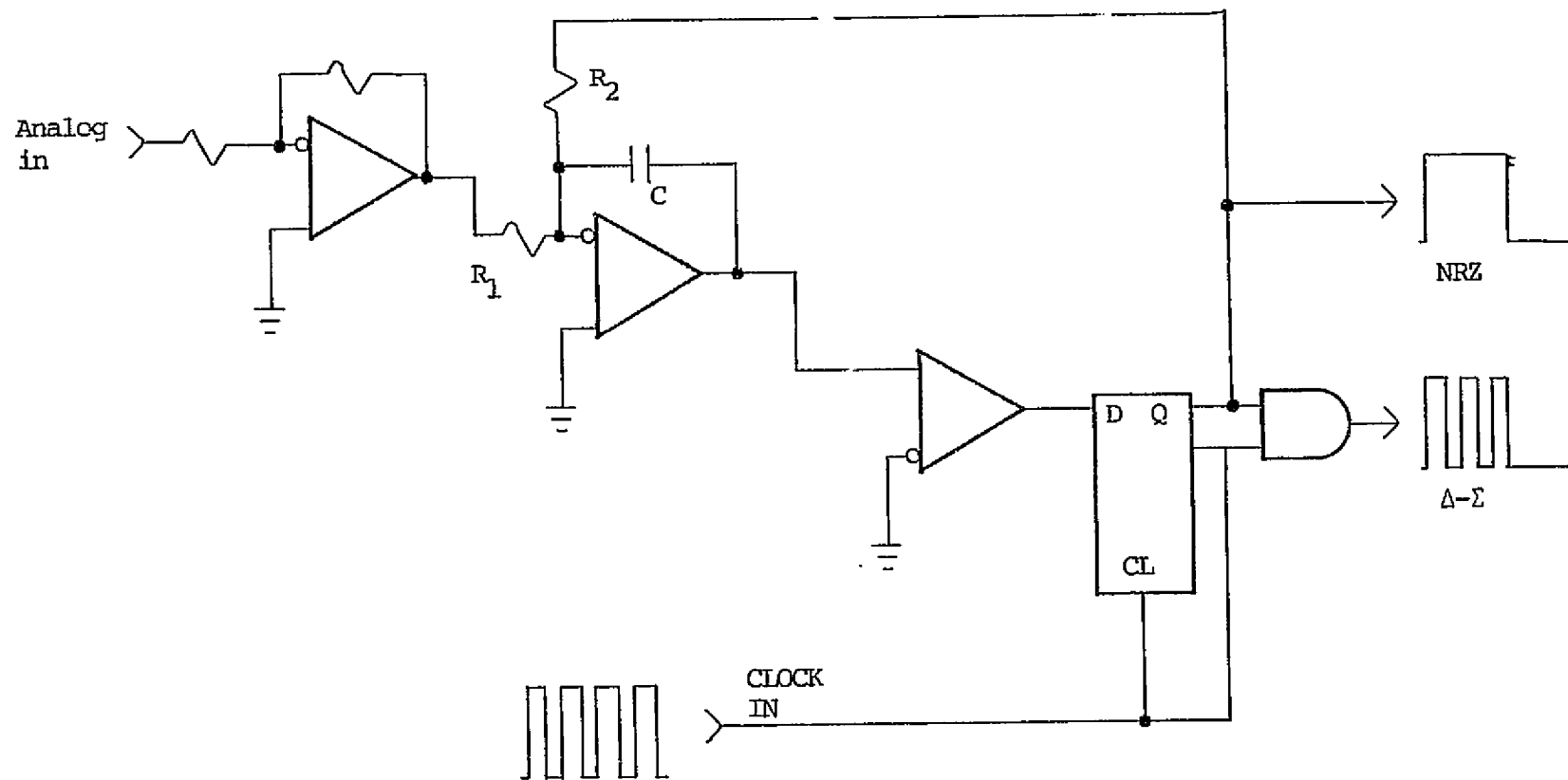


Figure 2. Delta Sigma Encoder

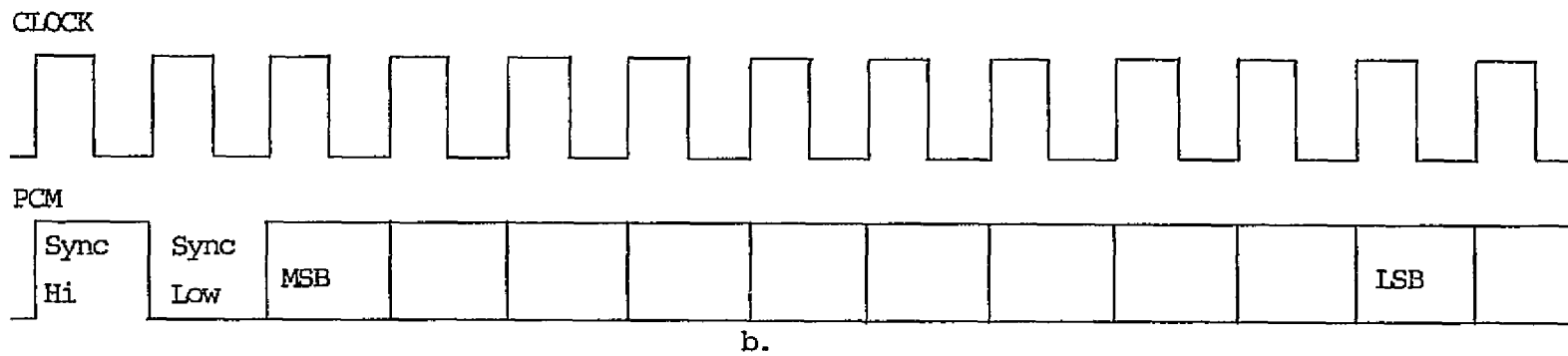
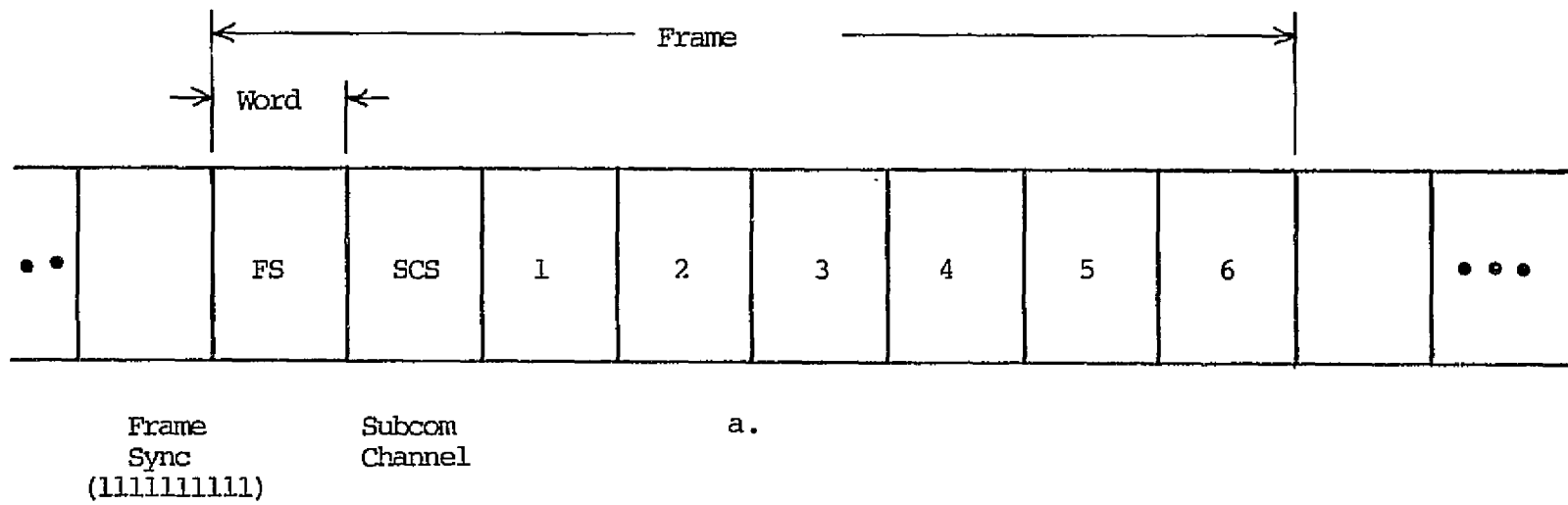
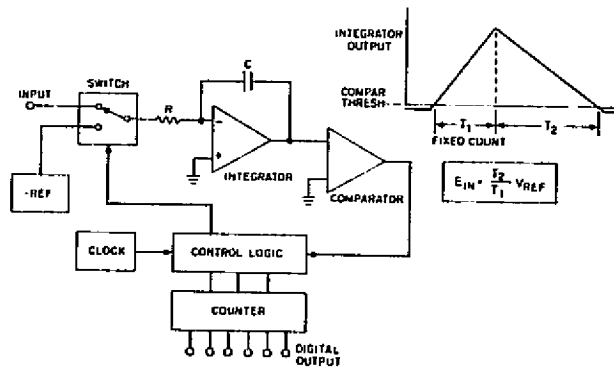


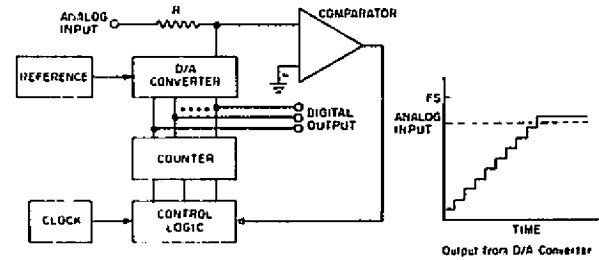
Figure 3. Format (a) and Timing (b) for PCM Encoder

nel system requires a clock frequency of at least 30 KHz for 100 Hz channel bandwidths. A PCM system was chosen because it did not require high-frequency clocking. Format and timing for the PCM encoder are shown in Figure 3. The analog signal is sampled, A-to-D converted, and serially shifted; frame sync and subcom sync are inserted at appropriate intervals.

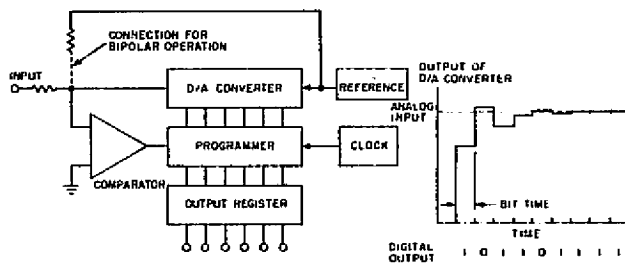
The techniques available for A-to-D conversion, shown in Figure 4, are dual slope, counter, successive approximation, and parallel. The number of channels and sampling rate dictate that the conversion must be completed in 190 to 200 μ s. The latter three techniques are fast enough for this. The counter method (PWM, counter) was used in the previous NASA/ARC encoder.⁵ This method requires a fast clock (5 MHz), and the actual construction included 22 CMOS integrated circuits and one hybrid crystal oscillator, and required more than 65 ma for its operation. (At 5 MHz, CMOS consumes more power than low power TTL.) The ARC encoder could not meet the specifications of minimum power. The parallel type converter potentially requires a similar amount of current in order to provide fast response time for the comparators. The successive approximation converter need run only at the bit rate frequency because it produces a serial output as it converts (at around 50 KHz in this case). CMOS dissipates



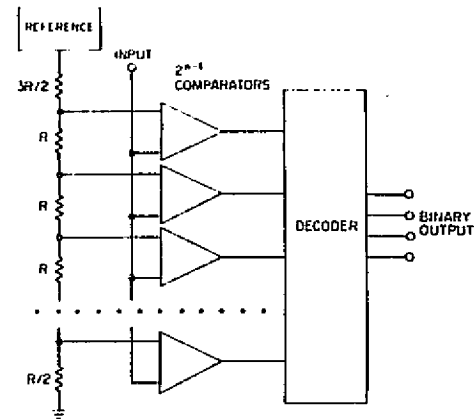
Dual Slope



Counter



Successive Approximation



Parallel

Figure 4. Analog to Digital Conversion Techniques

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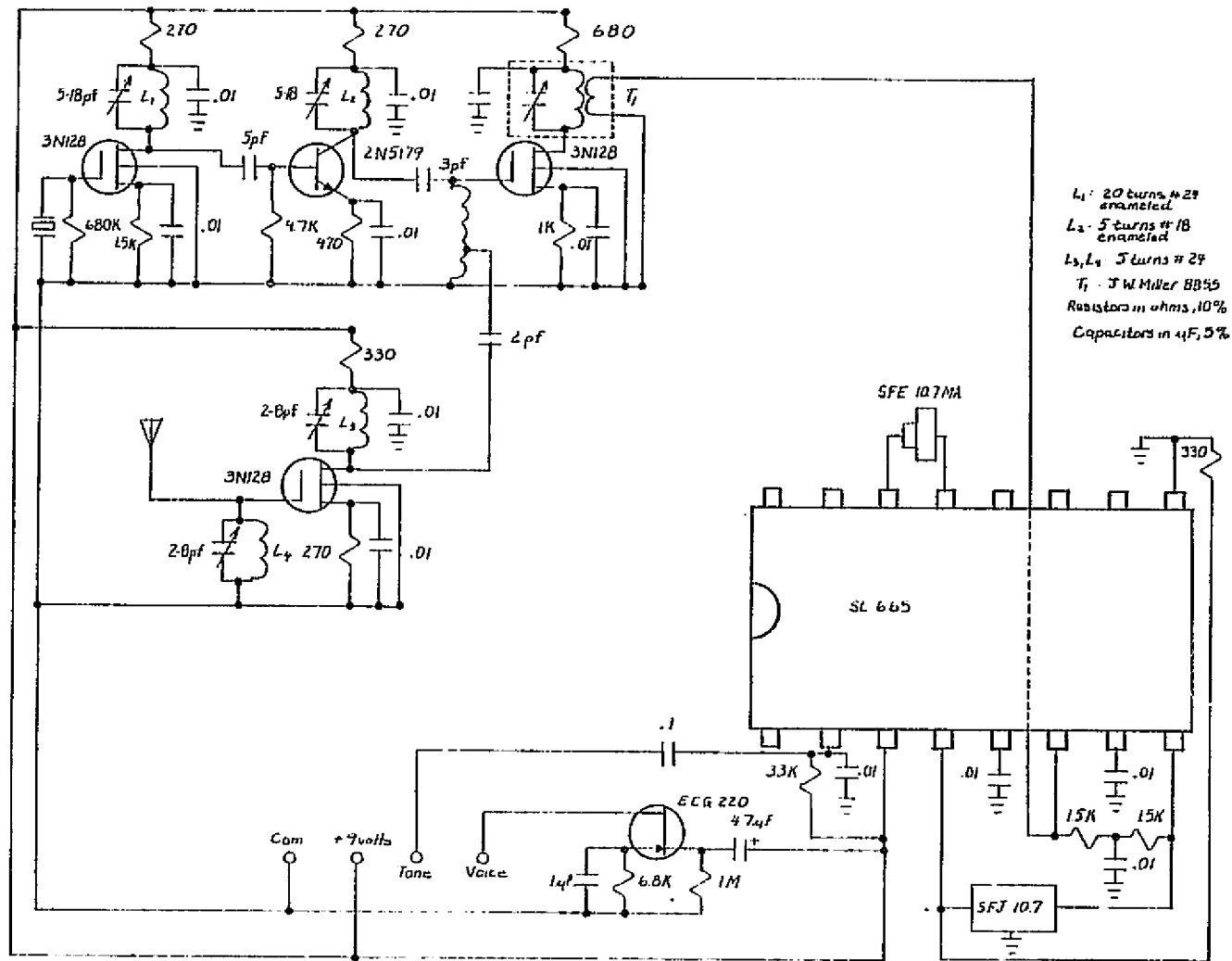


Figure 5. Portable Receiver

an average of 300 μ W at this frequency. Moreover, a monolithic converter of this type, which has a maximum current drain of only 4 Ma at 100 KHz, is available. A successive approximation conversion technique was used for the PCM encoder here.

D. Ground Base Station.

1. Receiver.

The receiver used in this work is a general purpose VHF receiver, with a frequency range between 30 MHz and 300 MHz, (Airborne Instruments Lab Model R-1283/GRC). It has both AM and FM detectors, and selectable IF bandwidths of 60 KHz, 300 KHz and 3 MHz.

2. PCM Decoder.

The decoder section incorporates CMOS and other low power integrated circuits. The front end of the decoder consists of a phase-locked loop circuit which converts the incoming Manchester bi-phase coded PCM data into non-return to zero (NRZ) data, at the same time providing the clock signal. These signals are fed into a monolithic CMOS D-to-A converter. The decoded channels are filtered by output active filters and provide six analog channels (350 Hz bandwidth) and seven low frequency channels for data.

3. Transmitter.

The transmitter used in the base unit is a commercial 0.5 watt crystal controlled narrow band FM transmitter

operating at 154.570 MHz (RepcO Inc. Model 810-041).

4. Tone Control Generator.

The control signal generator consists of tone-reed controlled sine wave generators. Two tone-reeds (100 Hz and 200 Hz) are used to encode the two bit control instruction word. The tone reeds stabilize the sine wave frequency to within 0.15%. The actual sine wave generator is a commercial unit (RepcO Inc. Part Number 810-024-02) compatible with the GBS transmitter. A modification of the tone generator was required, however, to implement a full 2-bit operation, because the tone generator would not accept both reeds simultaneously. Alternate transmission of the two tone signals at a switching rate of 1 Hz was close enough to simultaneous to be completely acceptable.

CHAPTER III
CIRCUIT DESIGN

A. Preliminary Design Considerations.

All circuits and systems described in this chapter were designed primarily for low power consumption, and secondly for minimum size. Factory packaged (because of their susceptibility to damage from static charges), low power CMOS devices were used for implementing digital functions. (Leadless Inverted Device (LID) packages would have been smaller, but these could not be obtained commercially, and flat-pack packages were employed.)

The r.f. links in the portable unit were designed to operate between 8 volts and 10 volts, so that a standard 9 volt transistor radio battery could be conveniently used. The analog portions were designed to operate at +5 and +2.5 volts so that small nickel-cadmium batteries could be used. (The level detector on the tone decoder can be easily modified for operation at other supply voltages.)

B. Portable Unit.

1. Receiver.

The receiver (Figure 5) front end (local oscillator, r.f. amplifier, and mixer) amplifies and converts the incoming 154.57 MHz to a 10.7 MHz IF frequency. The IF then is converted into an audio signal by a Plessey SL665 narrow

band FM chip. MOSFET transistors were because of their high input impedance, eliminating the use of extra components for impedance matching to reduce loading between stages. The 3N128 transistor was used because of its high gain-bandwidth product at relatively low current levels.¹⁵ The local oscillator consists of a MOSFET parallel resonant crystal oscillator followed by a Class C frequency tripler. The final output frequency of this stage is 143.87 MHz. An r.f. amplifier is included to increase the range of reception from the 500 mW transmitter used at the GBS. A non-resonant stub antenna was all that was required for reception up to 100 feet. A resonant, linear gradient wrapped antenna may be used for longer distances, but exhibits poorer behavior close to the subject. The outputs from the local oscillator and r.f. amplifier are combined via small (2 pF) capacitors at the gate of a MOSFET mixer. Because of the high impedance of the transistor input, this type of coupling is satisfactory.¹⁶ The square law behavior of the MOSFET makes it ideal for use as a mixer. A miniature 10.7 MHz IF transformer filters out all unwanted sum and difference frequencies. A conservative estimate of the gain of the front end section of the receiver is 60 dB.

The IF frequency is transformed into an audio output using a Plessey SL665 chip. This is a low power, thin-

base technology version of the industry standard RCA CA3075 chip. It performs the functions of an IF amplifier, a limiter, an FM discriminator, and an audio squelch amplifier. No tuned circuits or adjustments are required, and reliable operation is obtained in the range of 6 to 10 volts. The final audio output is approximately 10 mV (at 100 Hz), which is amplified by a JFET amplifier and applied to the earphone provided by NASA/JSC. Total current drain for this stage is from 10 to 15 mA, depending on supply voltage.

2. Transponder Control.

The transponder tone control section, (shown in Figure 6) of the receiver consists of three subsystems: tone decoders, decoder logic, and power control switches. The audio output from the receiver is first amplified by a section of a low power L144 operational amplifier, and then applied to one of two bandpass filters constructed from similar op amps.¹⁷ Dual integrator feedback is preferred over other schemes because the center frequency of the bandpass may be easily adjusted with one resistor. The tone decoders were designed for center frequencies of 100 and 200 Hz; they are followed by two one-shot multivibrators which provide a continuous output from the alternately switched tones transmitted from GBS.

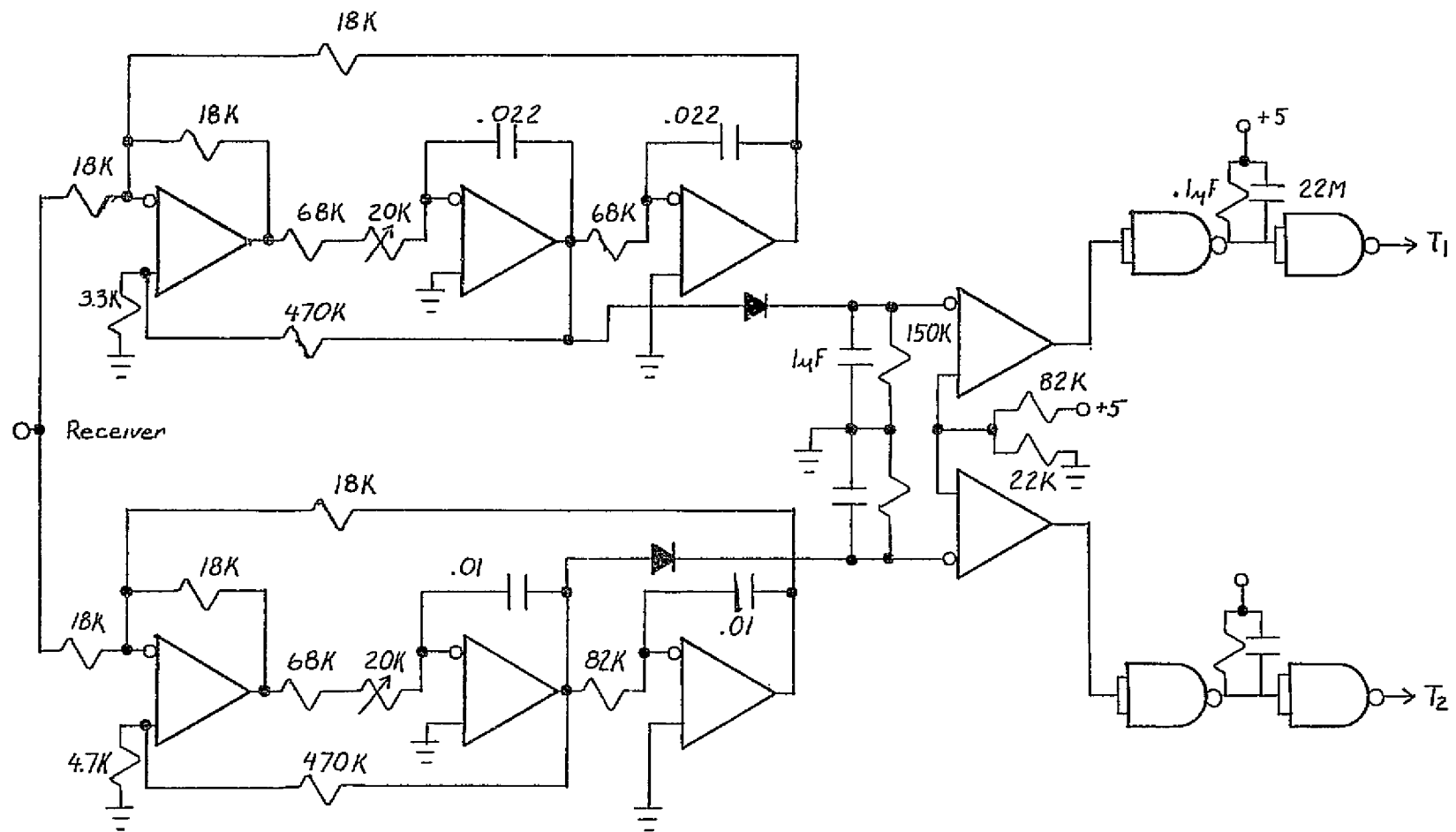


Figure 6. Tone Control

| INPUTS | | | OUTPUTS | | | |
|--------|----|-----|------------------|--------------------|------|-----|
| T1 | T2 | VOX | P _{rec} | P _{trans} | PCM | |
| | | | | | OPER | CAL |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 0 | 1 | 0 | 0 |
| 0 | 1 | X | 1 | 1 | 1 | 0 |
| 1 | 0 | X | 1 | 1 | 0 | 1 |
| 11 | 1 | 0 | 1 | 0 | 0 | 0 |
| 1 | 1 | 1 | 1 | 1 | 0 | 0 |

1 = True 1 = POWER ON
 0 = False 0 = POWER OFF
 X = Don't Care

Figure 7. Truth Table for Transponder Control

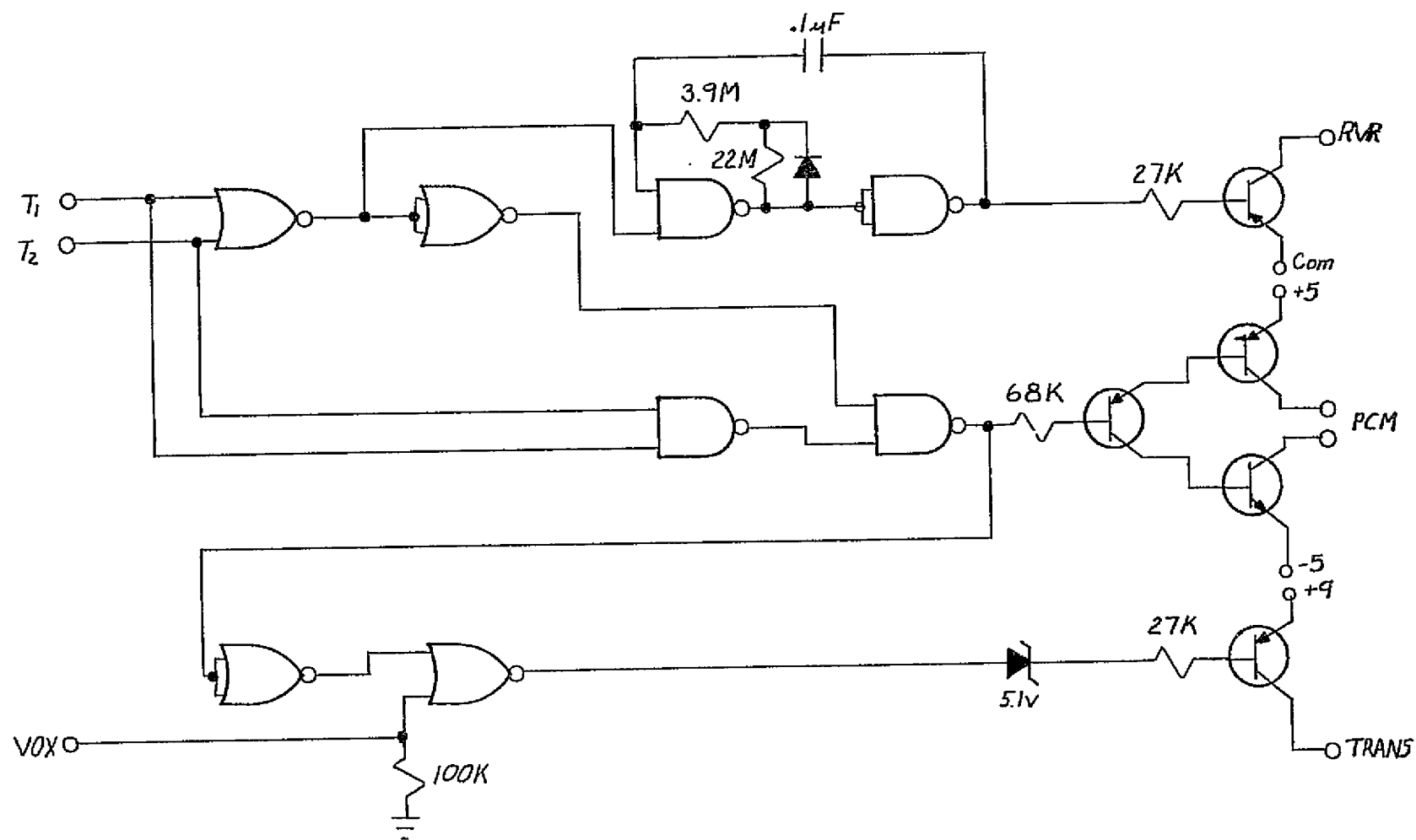


Figure 8. Transponder Logic and Power Control

Figure 7 shows in chart form the logic truth table required to implement the control functions described in Chapter II. Figure 8 is the circuit implementation of the truth table, using CMOS logic. Power is switched to the various subsystems, the PCM section requiring dual switches because of dual supply operation. In each case, a logical 0 applied to a switch results in a POWER ON condition. Total current drain for the transponder section is around 4.5 mA.

Figure 9 shows the VOX circuit: a standard op amp configuration with a Schmidt trigger level detector. The output of this level detector initiates a one-shot, eliminating switching transients and providing a smoother VOX operation; the one-shot has a two second period.

3. Signal Conditioners.

The front end of the PCM encoder consists of a switch network, a calibrate signal generator, and signal conditioners (the signal conditioner circuit is shown in Figure 10). The switches preceding each signal conditioner are CMOS bilateral switches connected in a double-pole, double-throw configuration. The control inputs of these switches are connected to the T_1 and T_2 tone control outputs (CALIBRATE and OPERATE). An OPERATE command switches the inputs of the signal conditioners to electrodes on the subject. A CALIBRATE command connects the calibrated generator to the inputs.

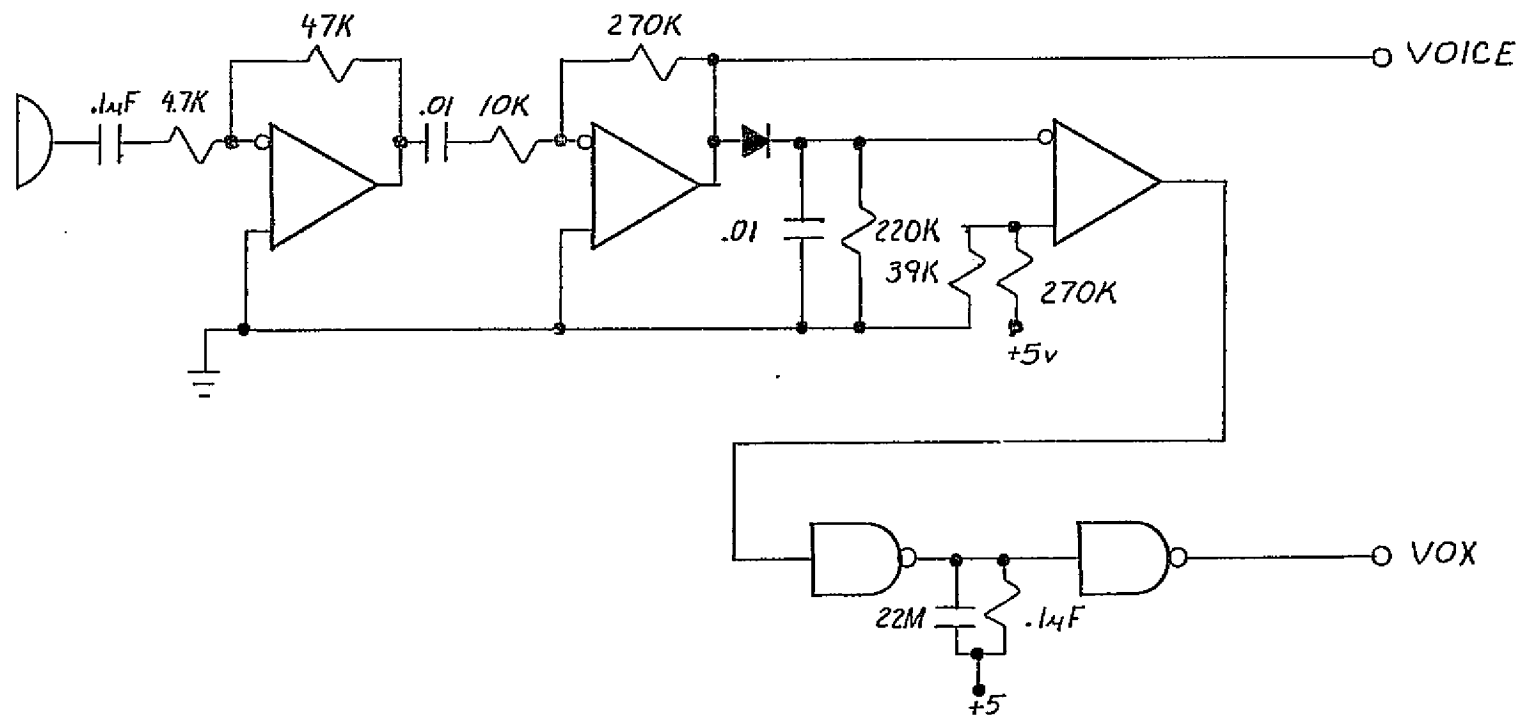


Figure 9. Voice Amp and VOX

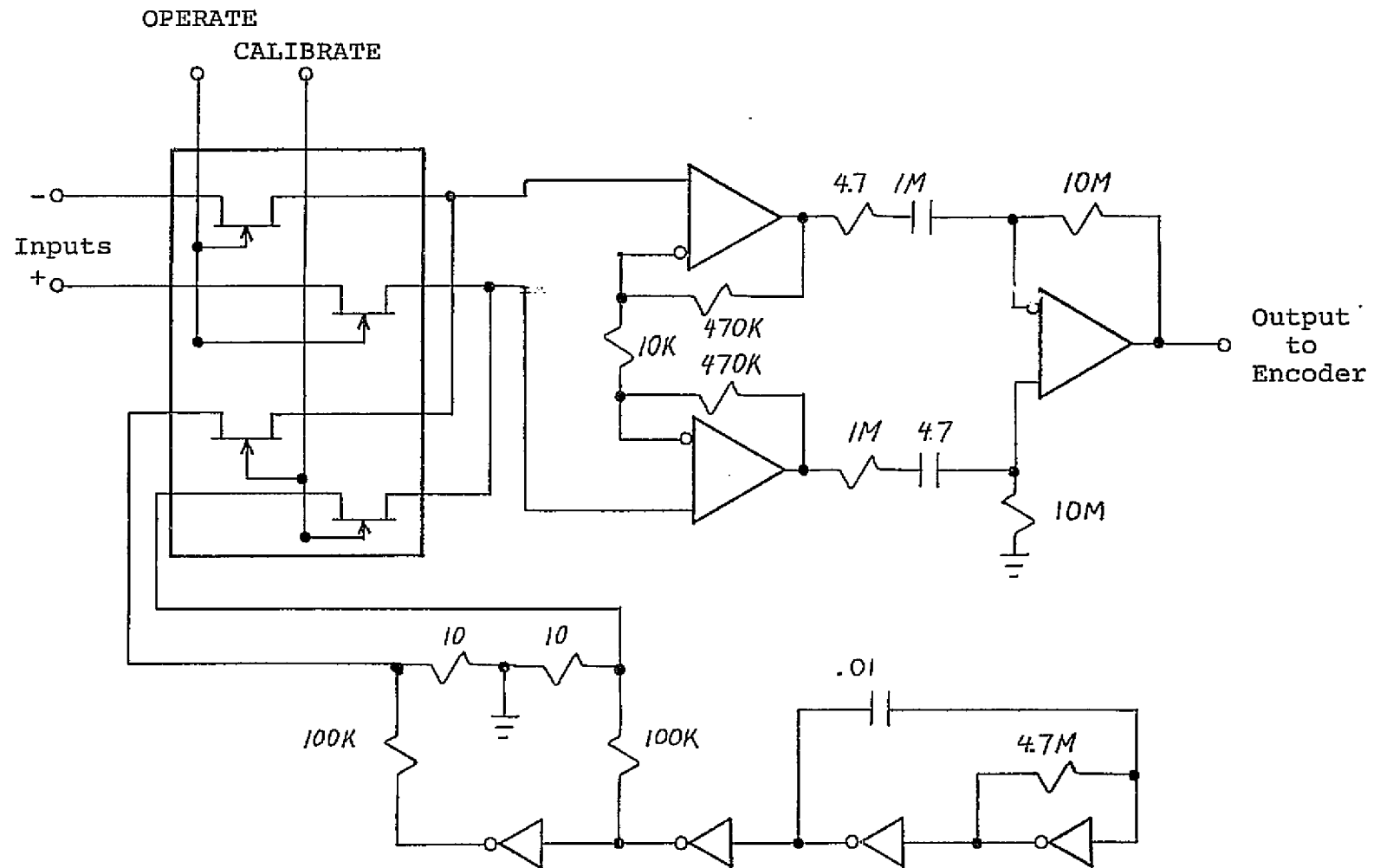


Figure 10. Signal Conditioners

The calibrate generator is a CMOS astable oscillator (approximately 5 Hz). A precision 1 mV differential signal is produced by the resistor divider network and the Zener diode voltage regulator. The signal conditioners each have a gain of 1000 and are AC coupled with a low frequency cutoff of 0.03 Hz. These amplifiers can be used directly with insulated electrodes,⁹ or the plug-in board may be removed if these electrodes have a sufficiently high output signal. Total current drain for the signal conditioner section is 400 μ A.

4. PCM Encoder.

The heart of the PCM encoder section (Figure 11) is a low power, CMOS monolithic A-D converter chip (AD7570). The chip is a self-contained successive approximation A-to-D converter which requires only the addition of a comparator (Z2) and an analog level shifting circuit (Z1). A section of an L144 op amp was originally used for the comparator, but it did not have a fast enough response time, so the faster, higher power SN311 was used.

The rest of the circuit consists of a clock oscillator (Z7) which may be tuned from 20 KHz to 100 KHz. The clock output is fed into the AD7570 chip (Z3) and provides the timing for the conversion and NRZ data output (pin 8). The chip has a BUSY output (pin 28) that goes high at the end of each conversion (after each 10 clock pulses corresponding to a 10-bit word). Because there is a 200 nsec delay

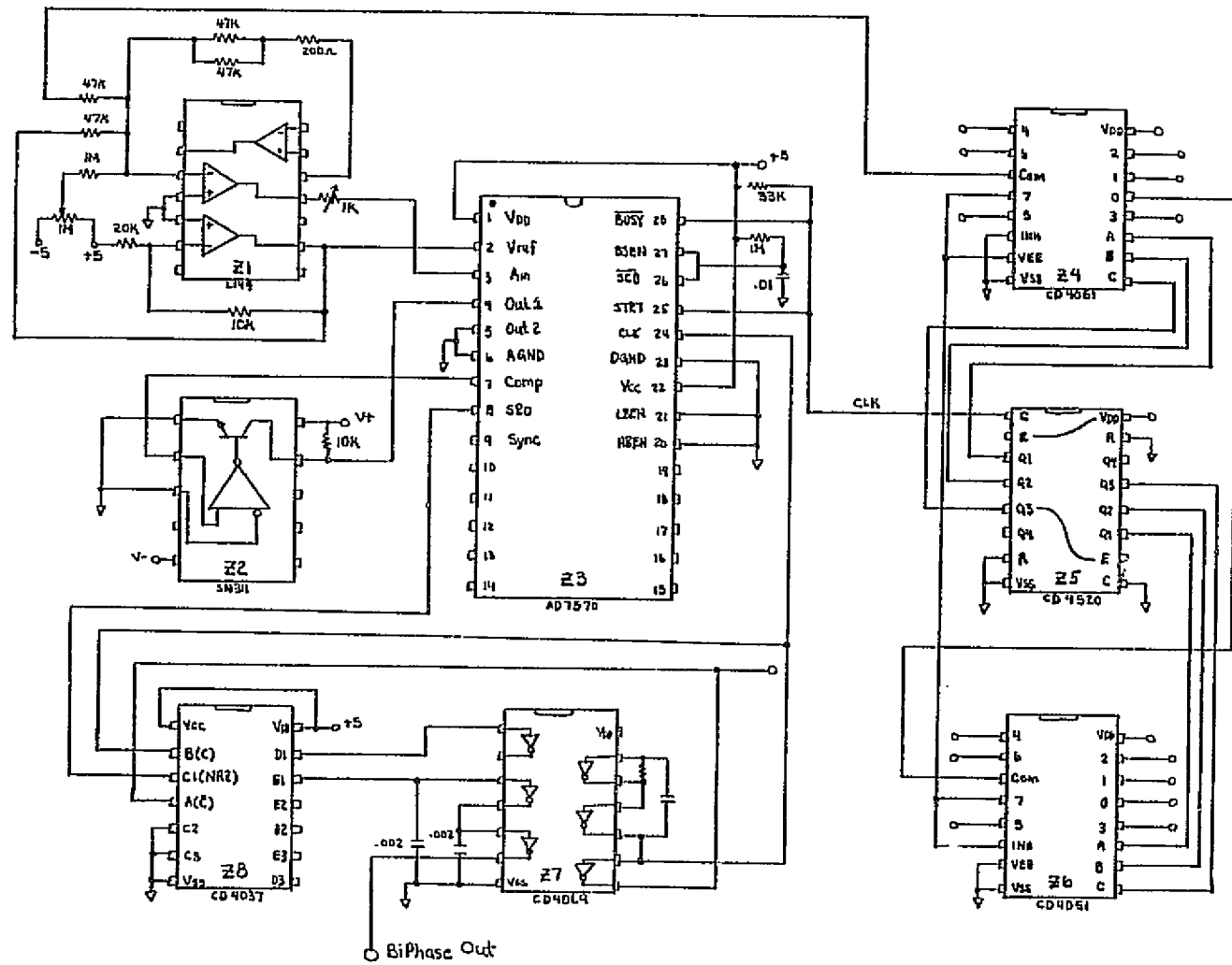


Figure 11. PCM Encoder

between the time the last bit goes low and the end conversion (BUSY) output, there will be a pulse at the output if the output is fed directly into the start input (pin 25). The pulse provides a repetitive start command for continuous operation; an RC delay circuit provides an initial start pulse when power is applied to the encoder. This type of feedback eliminates the requirement for additional timing chips. The output pulse from pin 28 is used to drive a dual counter (Z5), which cycles the two multiplexer chips (Z4 and Z6). These chips provide the time-division multiplexing between all signal conditioner inputs. Pins 7 on both chips are used for sync inputs; a string of ten 1s is used as a frame sync (Figure 3). Although others, larger units use Barker coding for synchronization, Barker code sync was not required here because of the low bit rate. The sync is generated by wiring both of the sync inputs (pins 7) to the -5 volt supply, producing a negative full scale output (1111111111) each time these inputs are addressed. This encoder was designed to convert input voltages on a ± 2.5 volt scale, so that any input voltage greater than -2.5 V will generate a sync (negative full scale) output. (Signal conditioners are run at only ± 2.5 volts, so that even in saturation, the amplifier output will be too low to generate a false sync signal.) Word sync is provided by the converter chip as a 1 bit followed by a 0 bit.

Chip Z8 is a circuit which converts the NRZ data from the converter chip into a Manchester bi-phase modulated signal. The tri-state data transmission scheme used in the first NASA design⁵ did not provide reliable reception and decoding at the base unit; in this receiver and decoder, the output NRZ data are coded (Figure 12a) with the clock and transmitted as two-state signals. Each time the NRZ data change state, the output is shifted 90° in phase. At the receiving end, the signal is decoded by using a phase-locked loop to recover the NRZ and synchronous clock signals (Figure 12b). Encoder current is around 2.5 mA.

5. Transmitter.

The transmitter is composed of a fifth overtone crystal oscillator, followed by two Class C power amplifiers; current drain for this circuit is around 20 ma. The crystal oscillator is frequency modulated by means of a varactor diode in series with the overtone crystal. Amplitude modulation for PCM transmission is obtained in the final power amplifier. Several methods for modulating the output carrier (around 90 MHz) were examined; the only method which provided a fast enough response time was switching power to the final power amplifier, at less than 100% modulation. Using less than 100% modulation has the advantage that the signal is never completely lost during the OFF period; enough signal is available for the automatic vol-

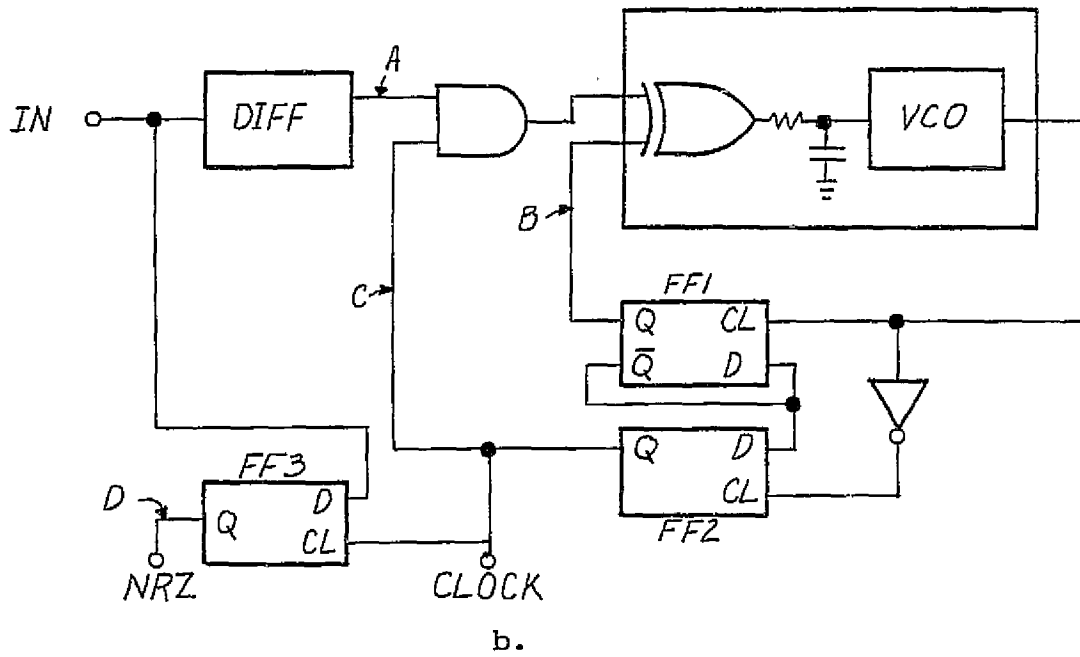
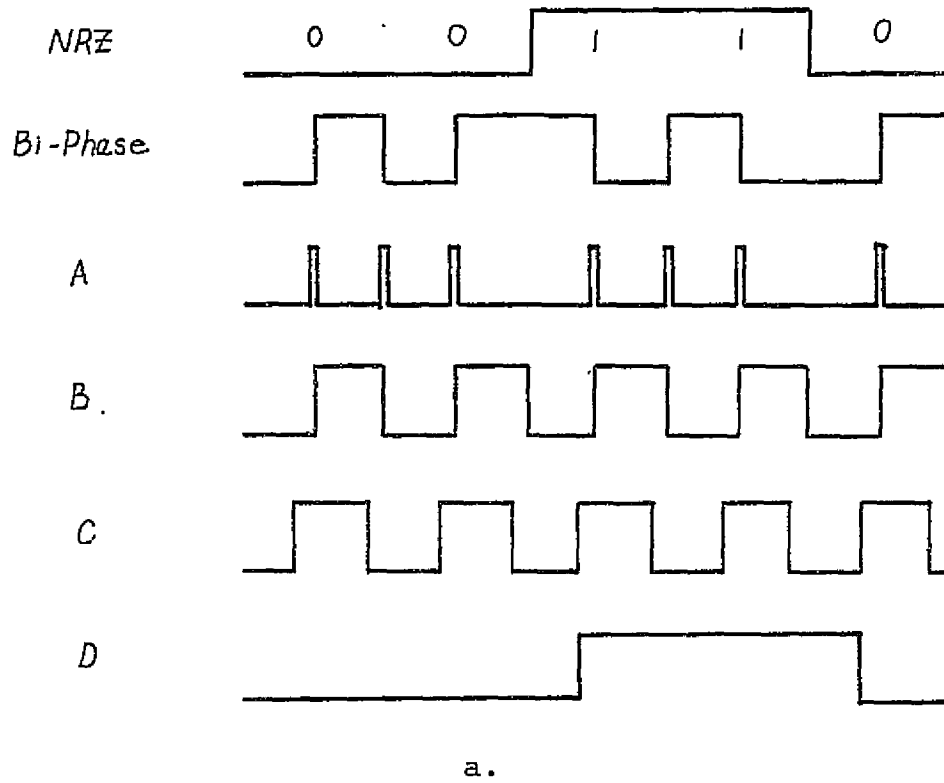


Figure 12. Bi-Phase Modulation. Format (a) and Decoder Timing (b).

ume control (AVC) to remain locked on. The modulated carrier is resonantly matched to a seven inch, wrapped, top loaded, linear gradient, short-tuned, flexible antenna (rubber ducky), which operates quite well close to the body. The transmitter assembly itself is mounted inside the ear-piece of the portable unit headset, to keep r.f. interference out of the PCM encoder. The portable transmitter circuit diagram is shown in Figure 13; Figures 14 and 15 are photographs of the circuit boards in the portable unit.

C. Ground Base Station.

The transmitter and receiver are commercial units, described in Chapter II.

1. PCM decoder.

The schematic diagram of the PCM decoder is shown in Figure 16. The output from the telemetry receiver is filtered and shaped by passing the received PCM data train through a 741 op amp (1 MHz bandwidth) followed by a zero-crossing detector (SN311). The output of the zero-crossing detector (logic levels 0 and 5 volts) is then fed into a phase-locked loop to recover the NRZ and clock signals. Referring again to Figure 12, the biphasic signal is fed into a dual edge detector (dual edge differentiator); the differentiated signal (A), which is twice the bit rate, is then gated into a CMOS phase-locked loop. The PLL VCO

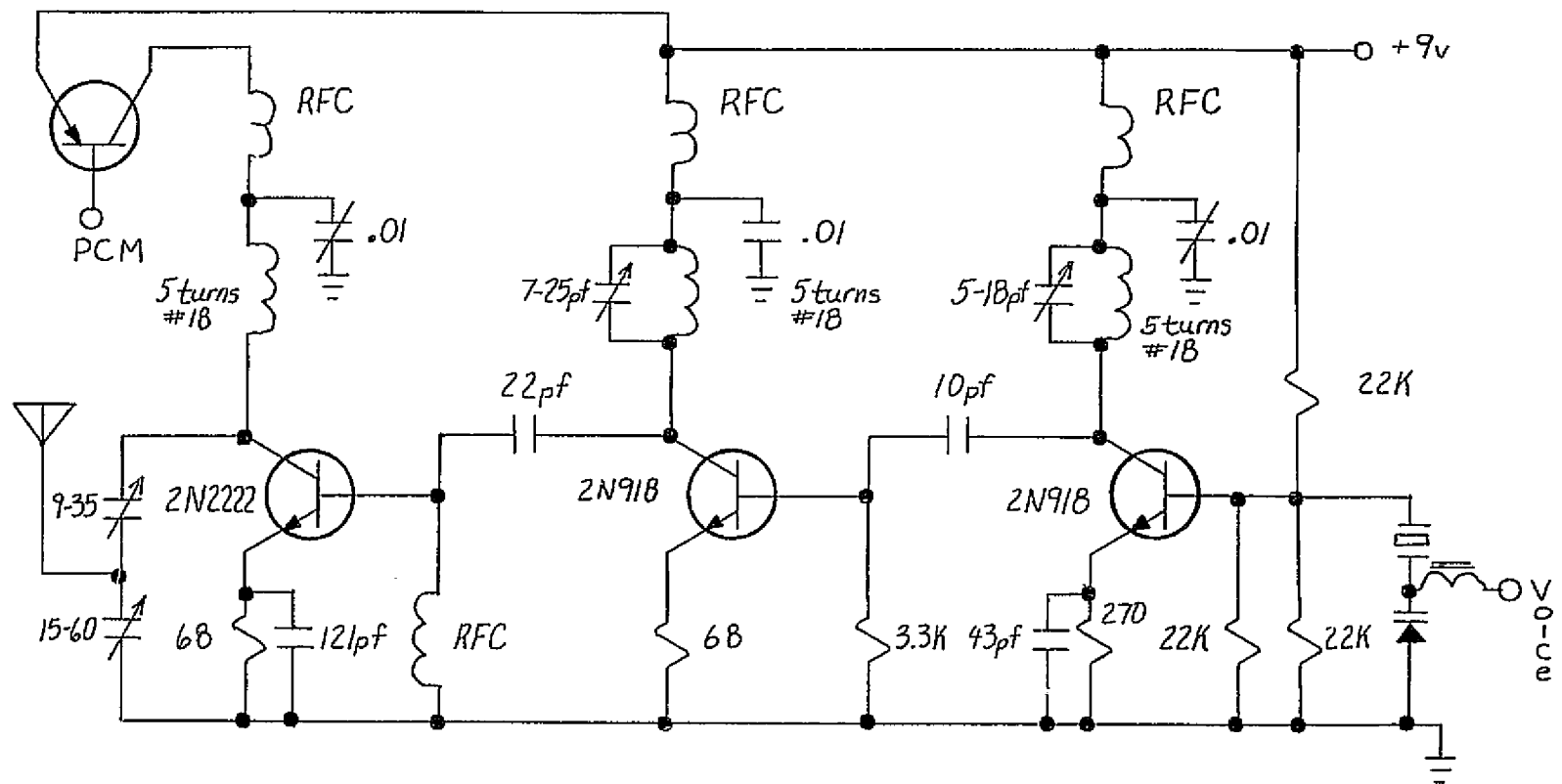


Figure 13. Portable Transmitter

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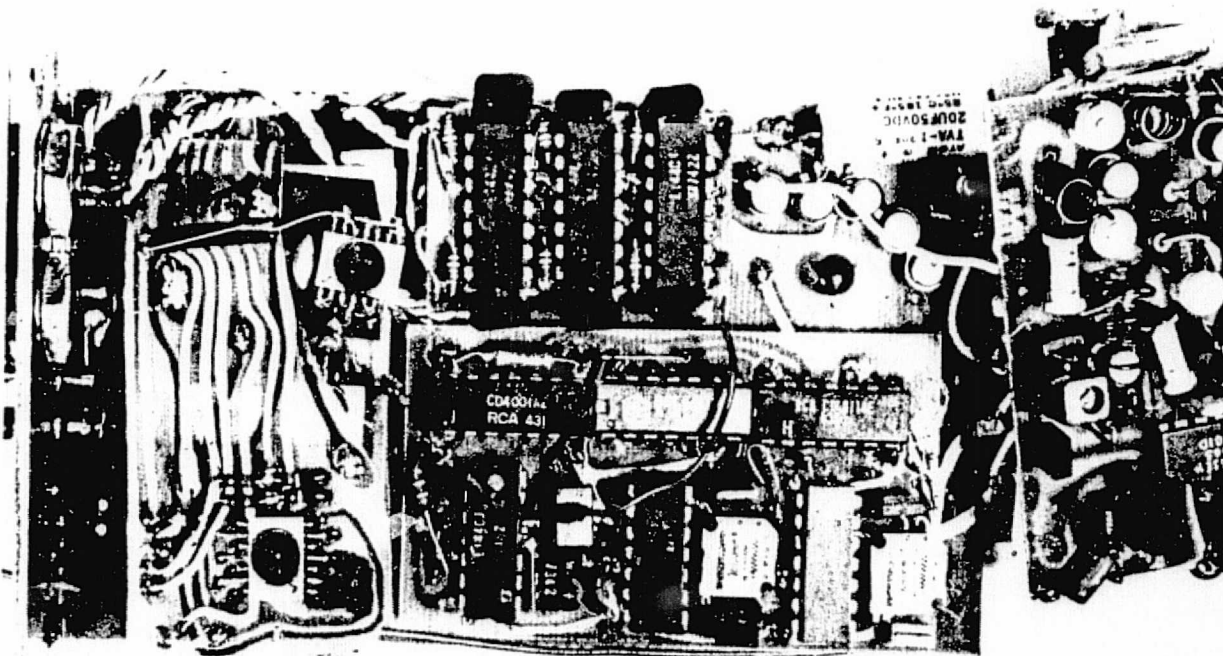


Figure 14. Detail of Circuit Board with Receiver Removed
to Expose Transponder Circuit



Figure 15. Transmitter

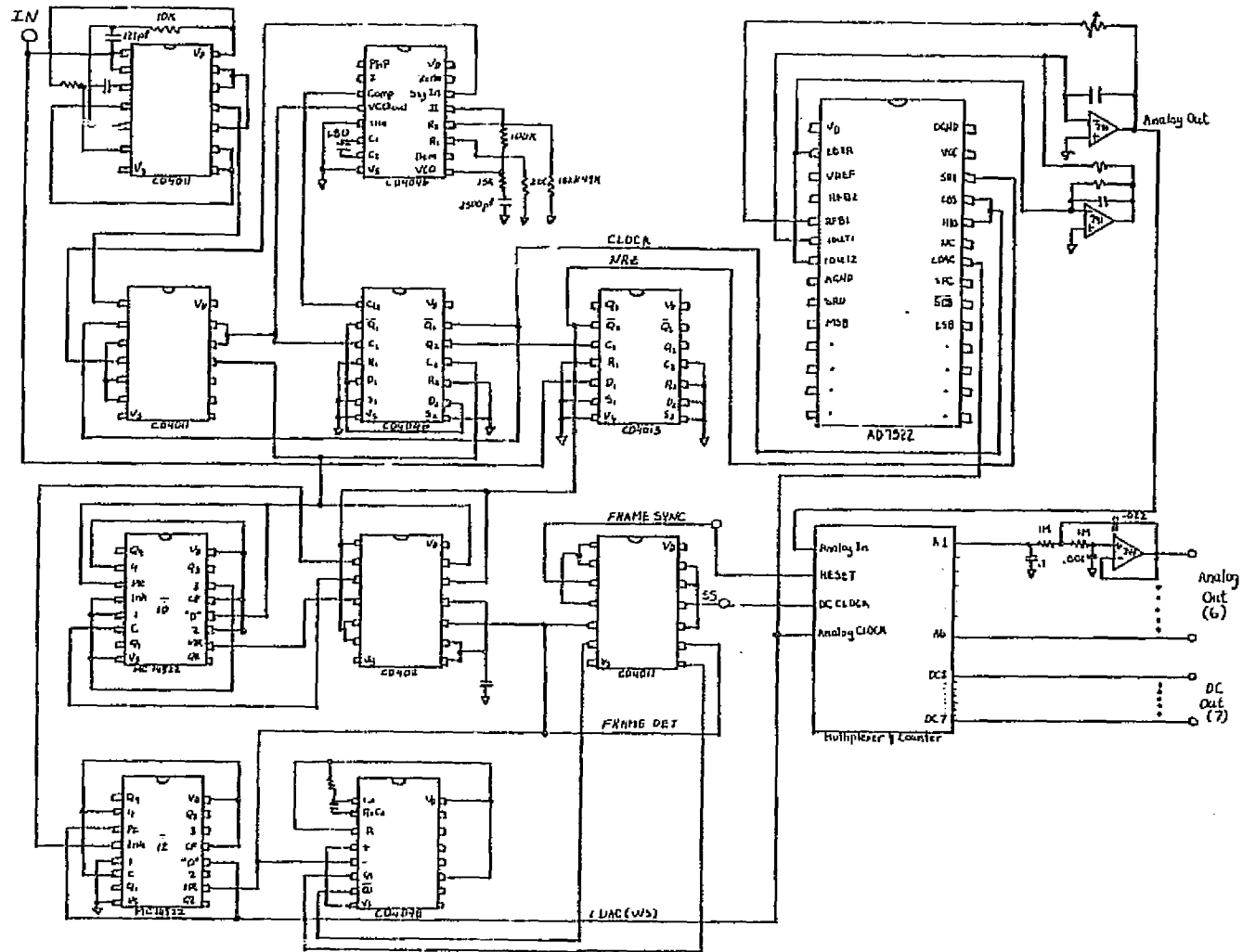


Figure 16: PCM Decoder

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output is fed into the clock input of FF1 which divides the VCO frequency by two. During the ON intervals, the PLL tracks the differentiated signal (A); during the OFF intervals the PLL remembers the last frequency present and still provides a clock output. The VCO output is inverted and fed into the clock input of FF2 whose data input is the inverted output of FF1. FF2 provides the necessary phase shift in signal (B) to obtain signal (C), the recovered clock signal from the split-phase data transmission. The output of FF3 is the recovered binary information from the phase information contained in the split-phase data. Usually a string of alternating 1s and 0s is needed initially to synchronize the phase-locked loop; otherwise the PLL may lock in on the wrong frequency. This is inconvenient from a hardware point of view, because if the signal were momentarily lost, a restart would be required. To circumvent this problem, the PLL was designed to have a narrow lock-in range, excluding completely the possibility of locking in on the wrong frequency. Lock-in time, therefore, is within a few clock pulses, and continued operation is assured even if there is a momentary loss of signal caused by reflections or similar effects.

The data from the phase locked loop circuit is passed through a divide-by-ten counter (Figure 16) which provides an output when ten logical 1s are counted (frame sync).

This output cycles analog gates similar to the ones in the portable unit, and also controls the monolithic CMOS D-to-A converter chip. The resulting decoded signal is fed into a series of active filters to remove the sampling frequency from the analog output.

2. Control Signal Generator.

The tone generator, tone reeds, tone select logic and audio stages in the GBS are located in a single circuit, shown in Figure 17. The tone select logic circuit consists primarily of an astable multivibrator with a frequency of 1 Hz; various inhibit and enable signals originating from the tone select switches are provided also. When switch S_1 is set for a logical 1 (+5 V), it inhibits multivibrator operation and allows one tone to be selected by switch S_2 . The multivibrator is enabled by setting switch S_1 back to a logical 0 (-5 V); because of the conditional connection of S_2 to S_1 , S_2 has no control in this mode.

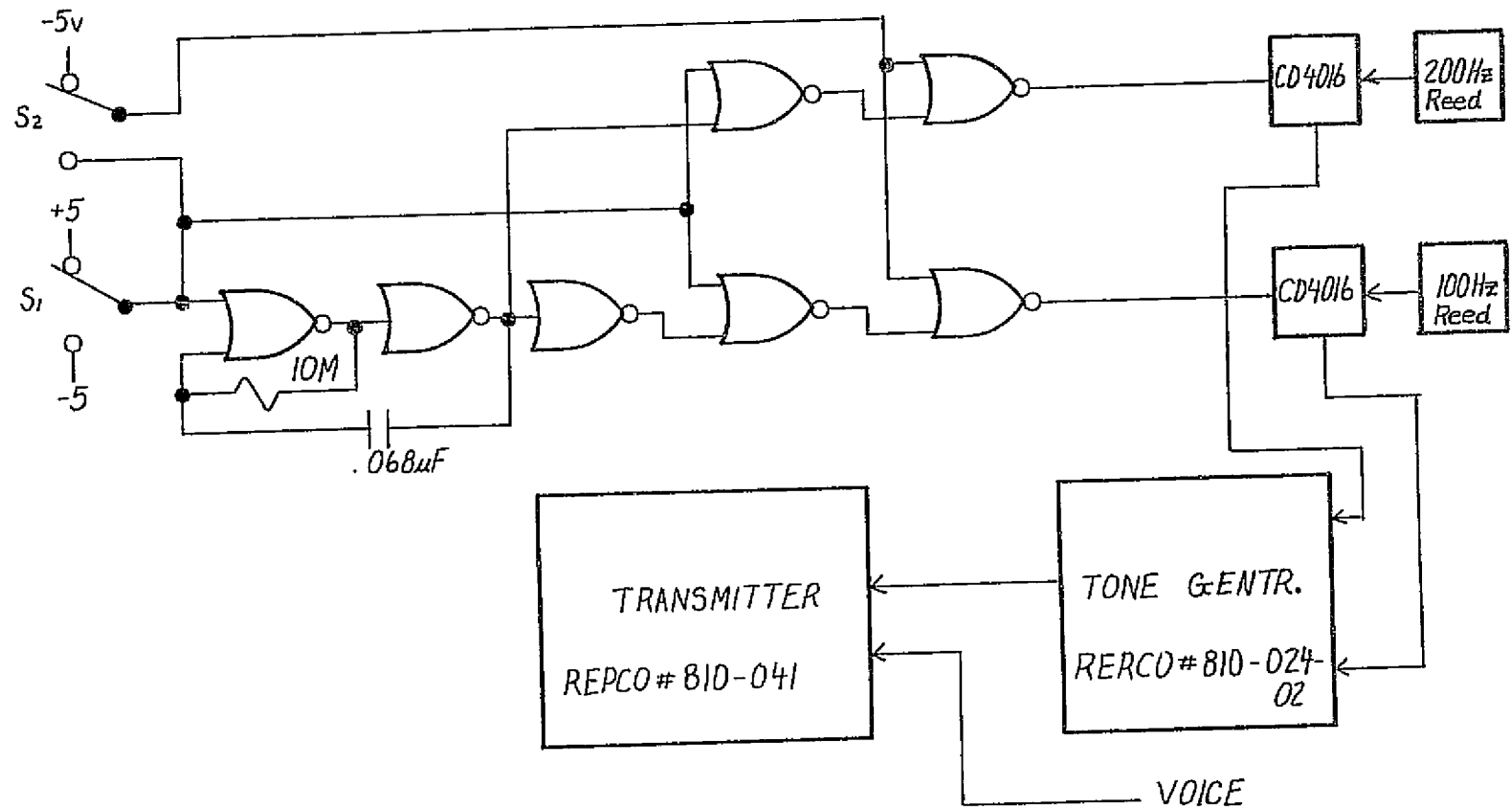


Figure 17. GBS Tone Control

CHAPTER IV
DISCUSSION OF RESULTS

Figures 18 and 19, respectively, are photographs of the GBS and the portable unit (with cover removed). Figure 20 shows the system in use; Figure 21 shows PCM data (300 KHz IF filter), and Figure 22 illustrates strip chart recordings of three channels of decoded ECG data.

The portable unit was designed with low power consumption as the primary criterion. Current drains for the various subsystems under operating conditions are: receiver, 10 mA at 9 volts; PCM encoder and transponder circuits, 7 mA; and transmitter, 20 mA at 9 volts. The total current drain is 37 mA; a substantial improvement over the previous design.⁵ The system can handle up to six analog data channels (approximately 350 Hz bandwidth) and seven dc data channels (30 Hz bandwidth); three of the analog channels are committed to Leads I, II, and III of ECG. Insulated electrodes may be used directly with the present system, or, if the electrode output signal is large enough, the plug-in signal conditioners in the portable unit may be removed. The transmitted voice signal has been received by GBS at distance of several hundred feet, but because the portable receiver's range is much less than this, the portable transmitter cannot be transponded ON at such long ranges, and the range limit for the PCM signal

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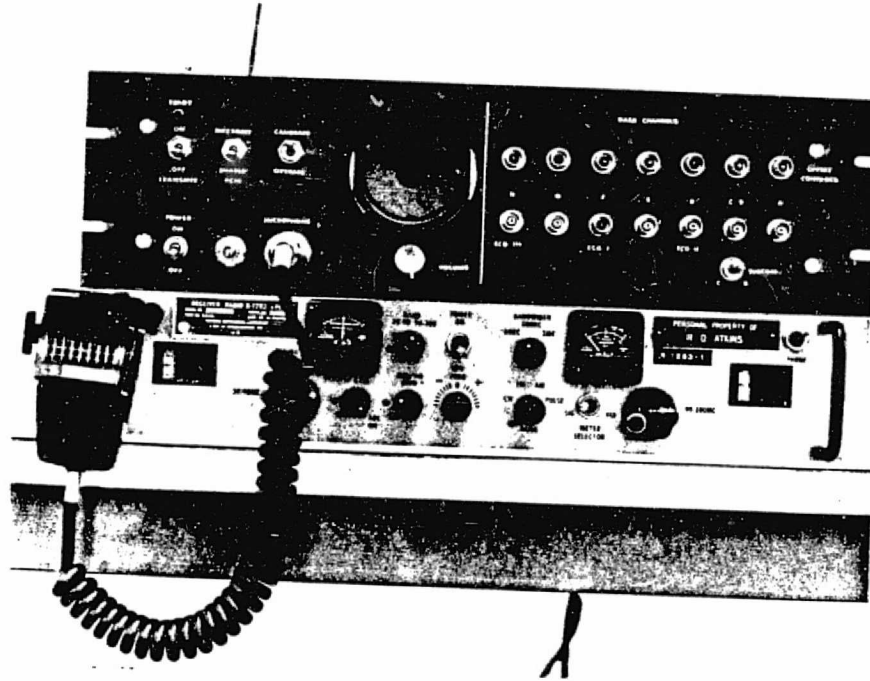


Figure 18. Base Unit with Telemetry Receiver

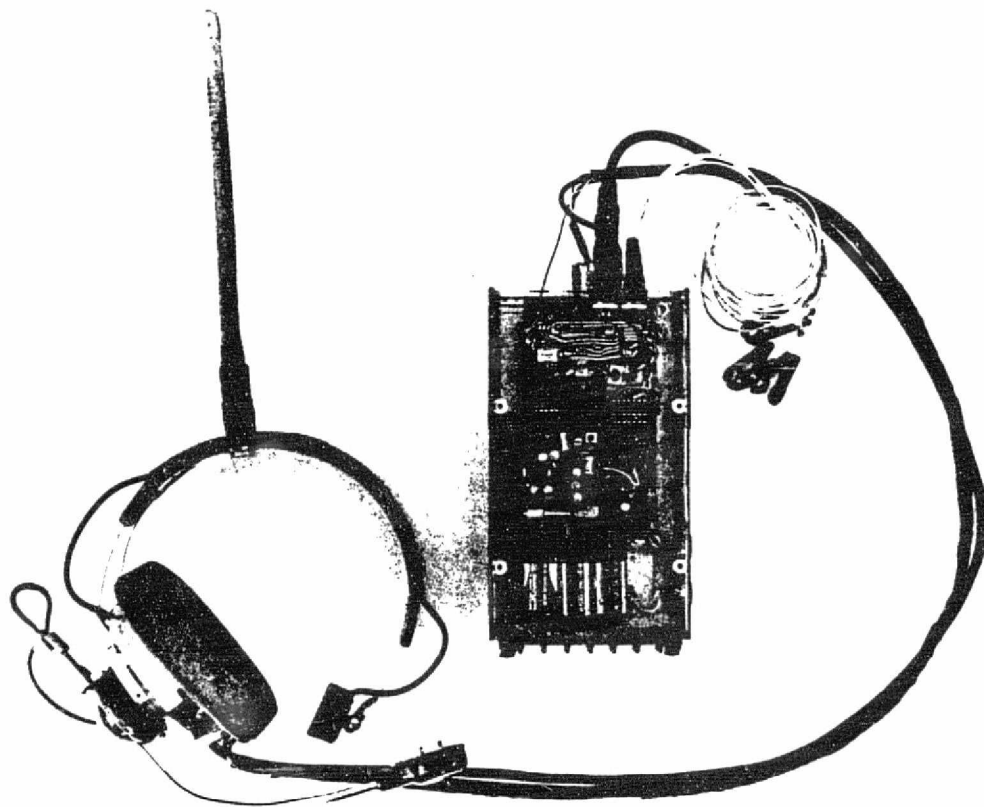


Figure 19. Portable Unit with Cover Removed



Figure 20. Portable System in Use

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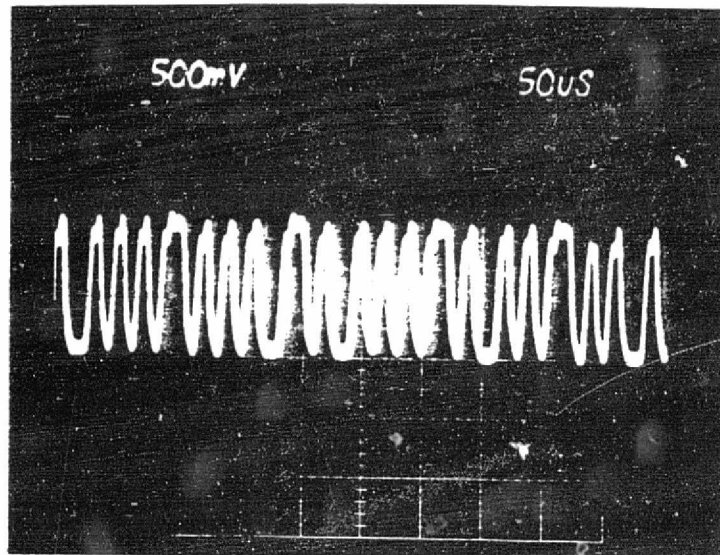
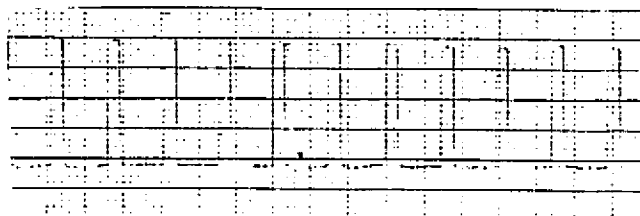
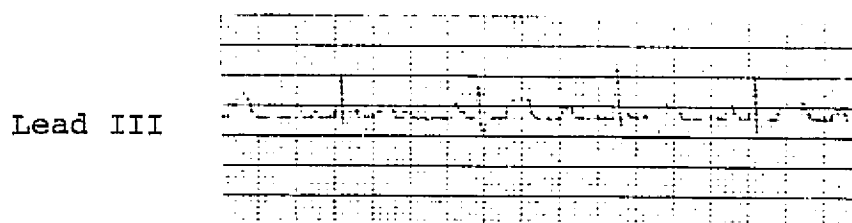
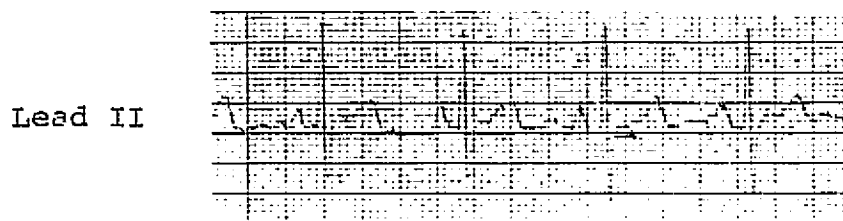
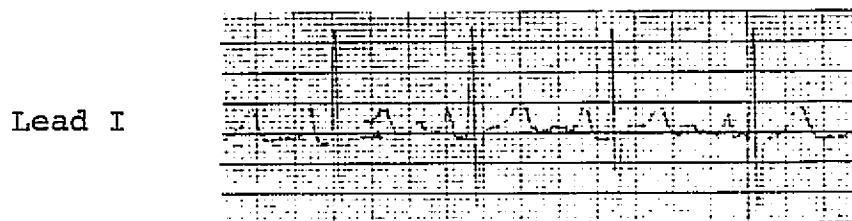


Figure 21. Received PCM Data



Calibrate signal present at the signal conditioner inputs in the CALIBRATE mode. (The dashed line represents voltage zero.)

Vertical Scale: 1 mV per cm
Horizontal Scale: 25 mm per sec

Figure 22. Received and Decoded ECG Data

could not be obtained. The entire circuit for the portable unit is quite small, considering its complexity, its dimensions being 2.5 inches by 4.5 inches by 1.25 inches. The packaged unit is larger (4 inches by 7 inches by 1.75 inches), the increased size being the result of an oversized package, the only one conveniently available.

CHAPTER V
CONCLUSIONS

A fourteen channel (six analog and seven d.c. data channels, and one voice channel) physiological data telemetry system has been designed, built, and tested. The portable unit was equipped with three leads of ECG (I, II, and III), calibration channels and two-way FM voice communication. Ground base station has complete control of power to all subsystems in the portable unit. The major design problem in the previous NASA unit⁵ (wideband, crystal controlled FM transmitter with tri-state logic) was addressed by using a crystal controlled AM transmitter and Manchester bi-phase modulation. A modified phase-locked loop circuit was used to decode the data, remaining in operation even when the signal from the portable unit was interrupted. This system represents a substantial contribution to the state-of-the art, inasmuch as it combines portability, small size, low power and digital transmission.

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