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A MINIATURIZED DIGITAL TELEMETRY SYSTEM FOR

PHYSIOLOGICAL DATA TRANSMISSION

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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

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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 con-
ventional technology. In a second design,[5] size and power
were reduced; however, the second design required the incor-
poration 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 implementated, 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 trans-
ponded 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 con-
trol of transmission from the subject was to prevent inter-
ruption, by the subject, of transmission in crisis situa-
tions. (A subsidiary of power control by GBS was the re-
duction of power consumption in unused subsystems.)

The most accurate telemetry system is one which is
independent of the type of radio link employed. By con-
verting input physiological data into a digitally coded
word before transmission, nonlinearities which arise dur-
ing 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 scheme[8] (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 per-
formance of the system, and a discussion of its applica-
tions.

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 formating 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 consistant 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
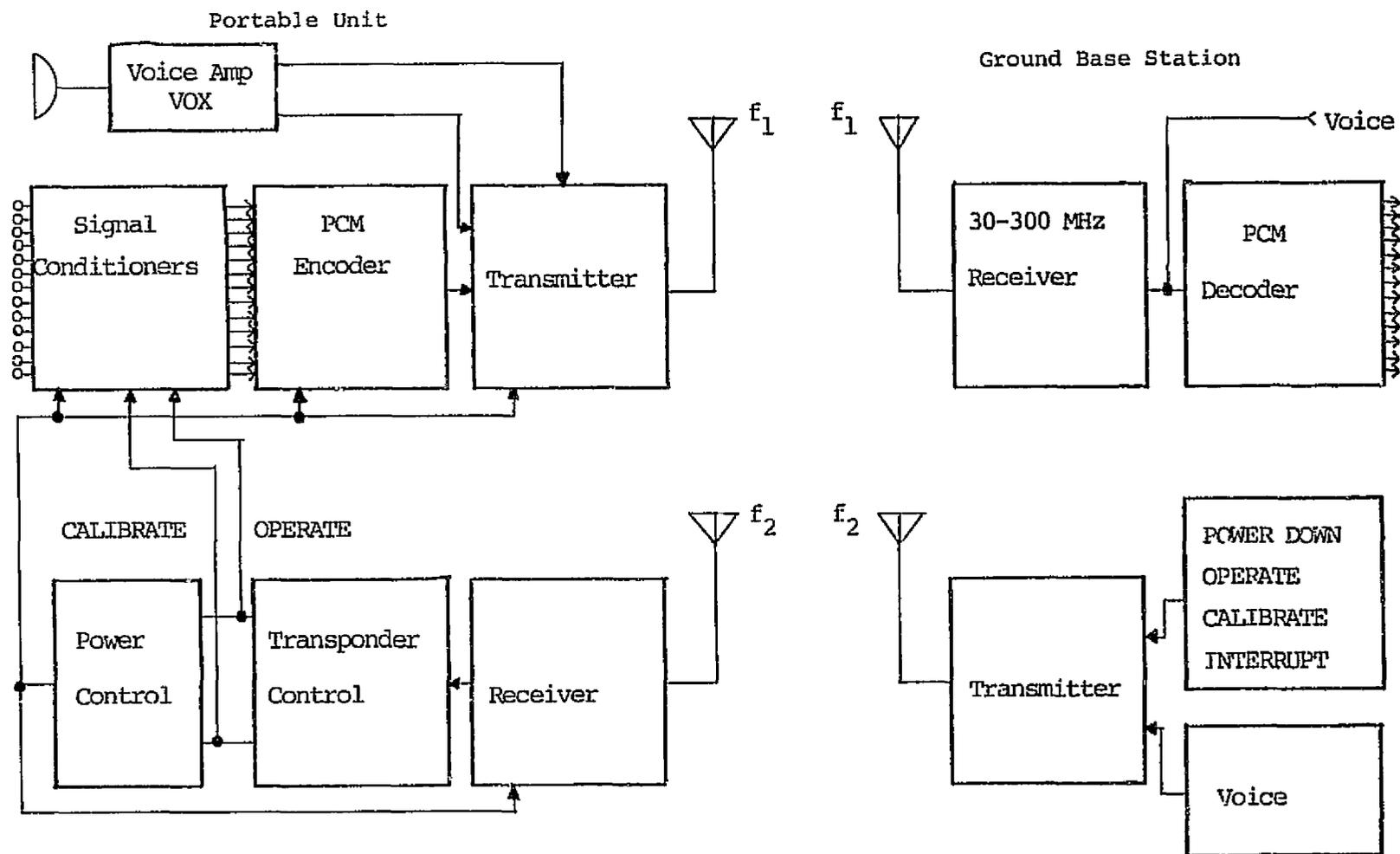
Figure 1. System Block Diagram

control, to permit voice transmission. Transponder con-
trol of the portable unit is obtained by transmission of
two tones from the base unit, providing four modes of con-
trol 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 sig-
nal 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 samp-
ling 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 design[5] 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 ampli-
fiers, the last being amplitude modulated by the two-state
PCM signal. The original NASA requirement that the trans-
mitter be crystal-controlled and frequency modulated at
the same time cannot reasonably be satisfied with a minia-
turized, low power design when only one transmitter is
used to transmit two different signals with widely differ-
ing characteristics. Introducing a linear frequency devia-
tion of 5 KHz into a crystal controlled oscillator is rela-
tively 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 design[5] 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 possi-
bilities for meeting the requirement of a single crystal-con-
trolled FM transmitter were considered. First, two oscil-
lators 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 accept-
able 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 catagories: subcarrier 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, $\Delta-\Sigma$, 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; $\Delta-\Sigma$, because of its larger bandwidth, is a close second.[11,12,13,14] $\Delta-\Sigma$ 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-
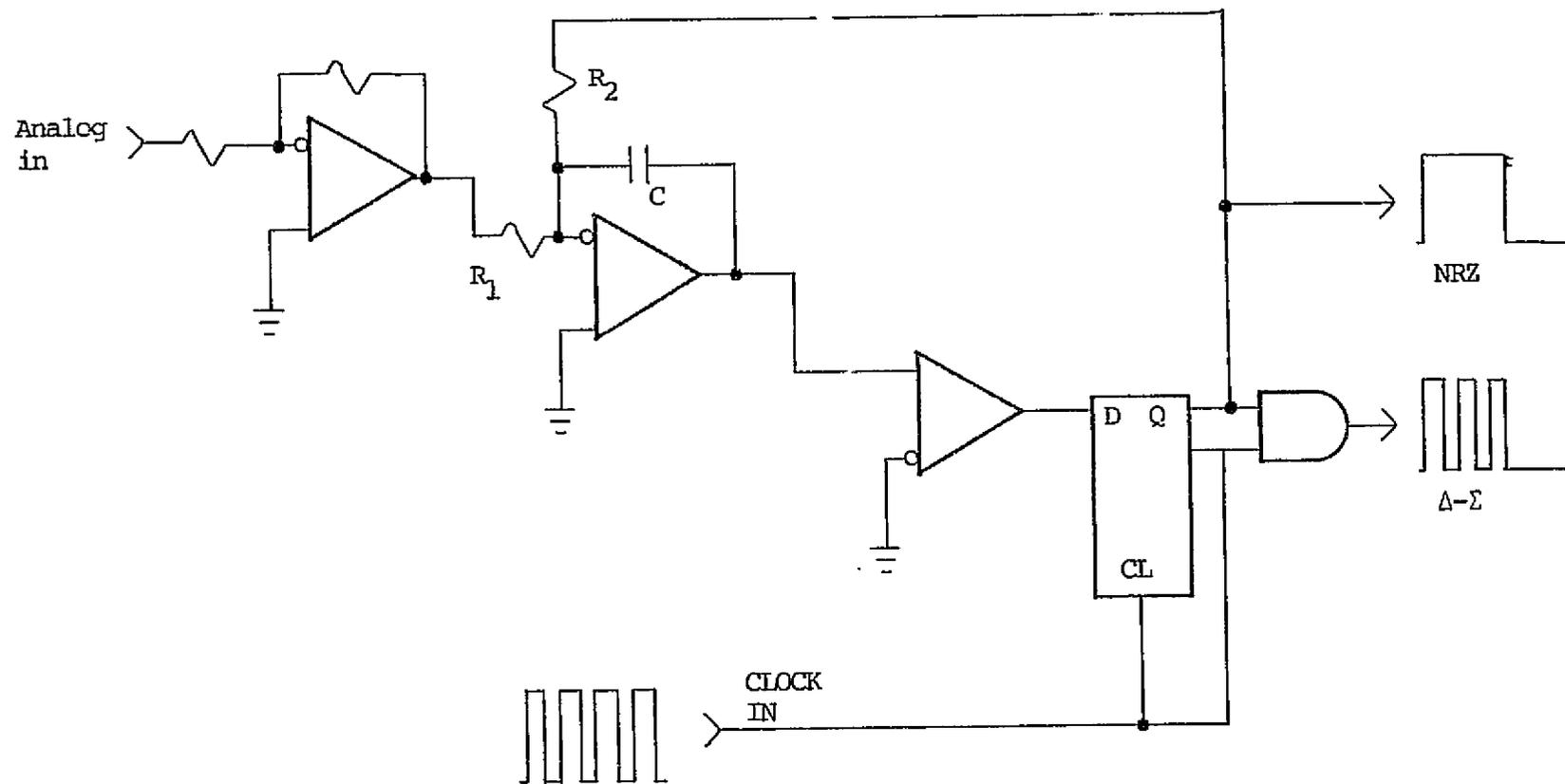
Figure 2.   Delta Sigma Encoder
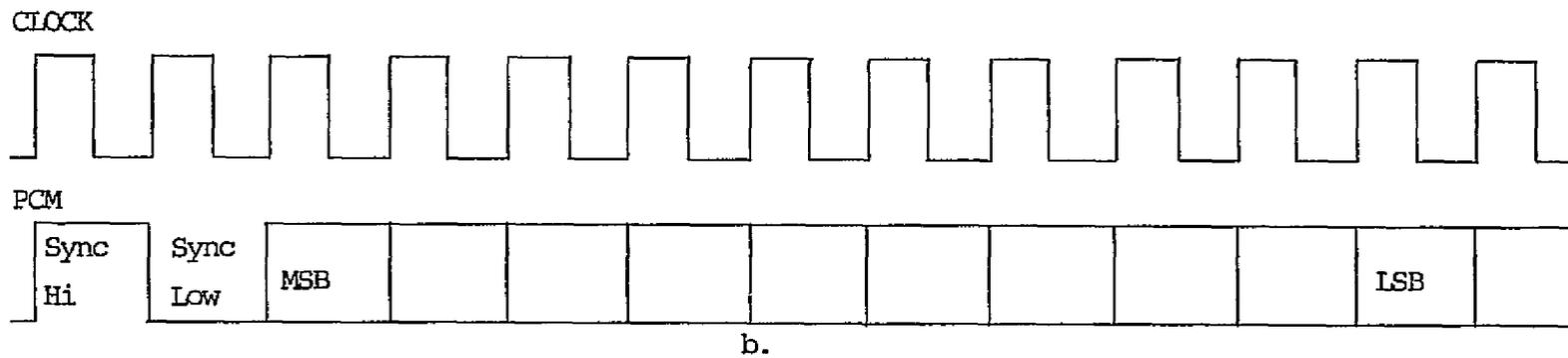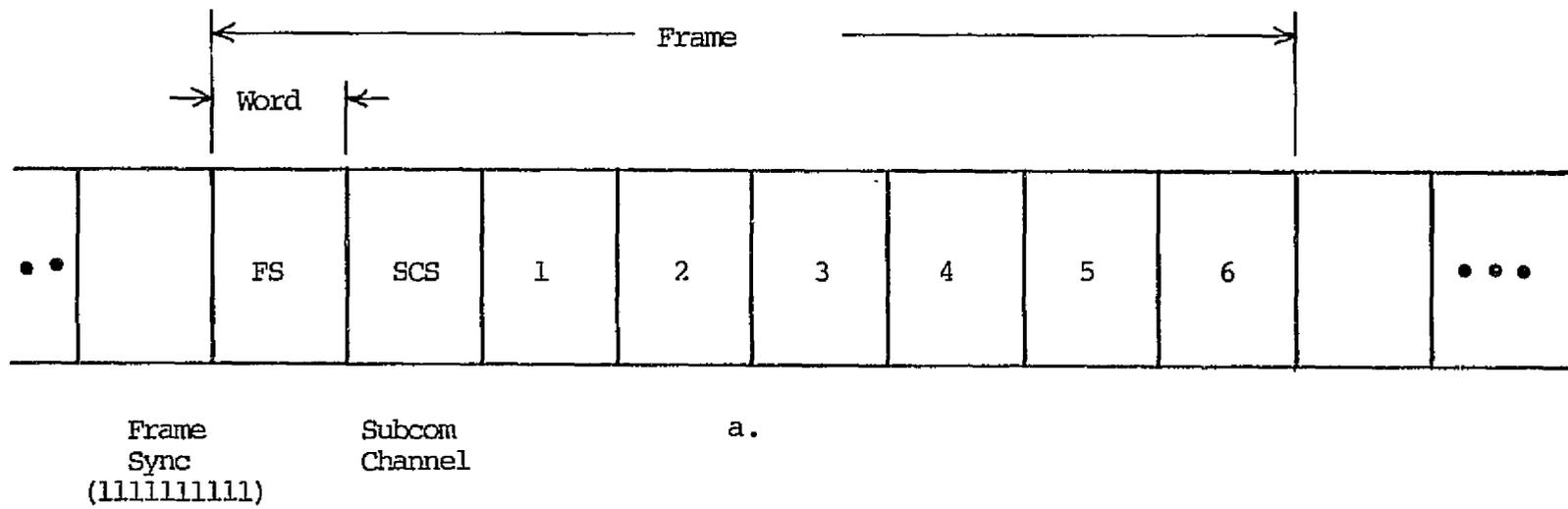
Figure 3. Format (a) and Timing (b) for PCM Encoder

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 appro-
priate intervals.

The techniques available for A-to-D conversion, shown
in Figure 4, are dual slope, counter, successive approxi-
mation, and parallel. The number of channels and sampl-
ing rate dictate that the conversion must be completed
in 190 to 200 μs. 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 re-
quires 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 con-
verts (at around 50 KHz in this case). CMOS dissipates
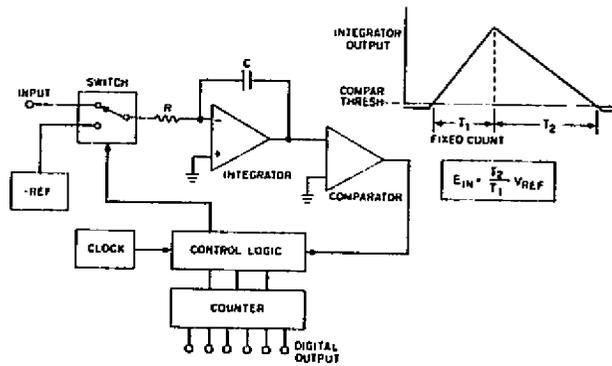
Dual Slope
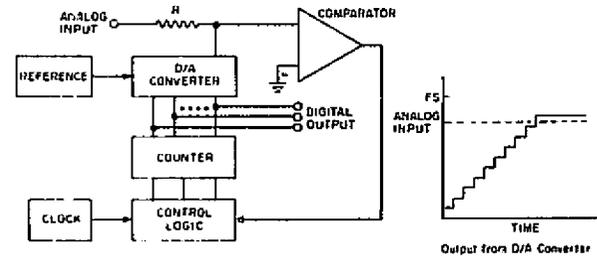
Counter
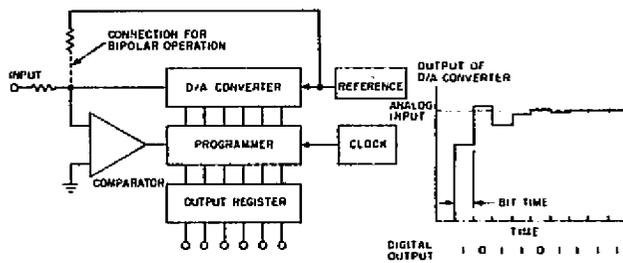
Successive Approximation
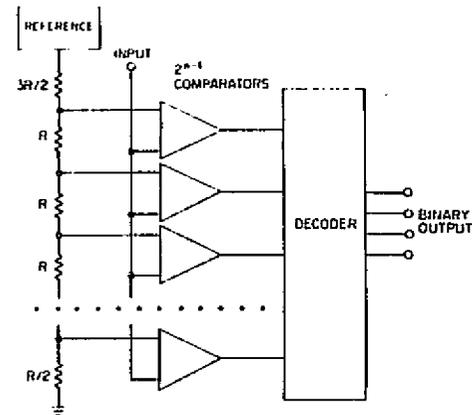
Parallel

Figure 4. Analog to Digital Conversion Techniques
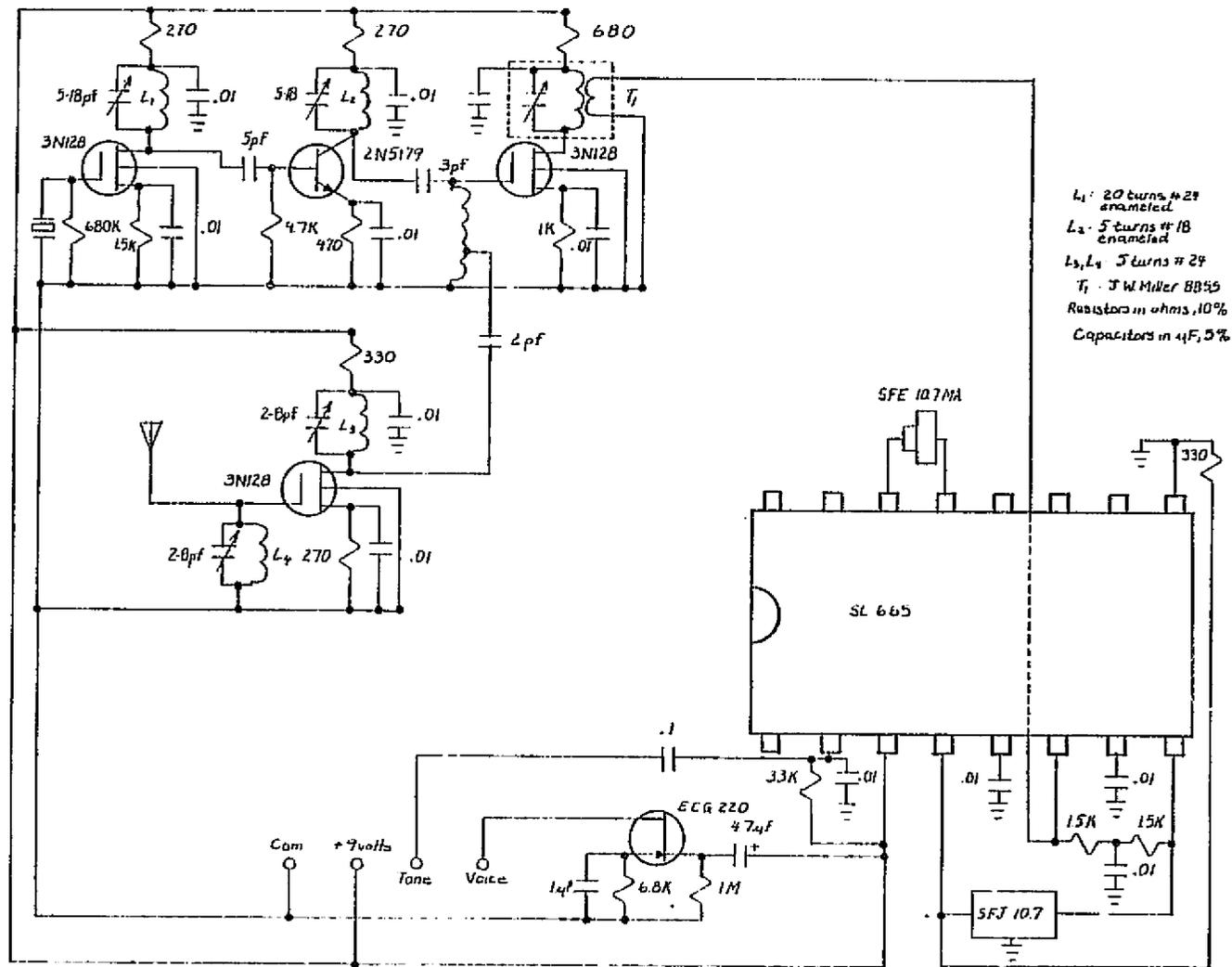
Figure 5.   Portable Receiver

an average of 300 μW at this frequency. Moreover, a mono-
lithic 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 out-
put 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 implementating digital
functions. (Leadless Inverted Device (LID) packages would
have been smaller, but these could not be obtained commer-
cially, 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 modi-
fied 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 in-
coming 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 impedence, eliminating the use of extra compon-
ents for impedence 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 ex-
hibits 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 impedence 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.
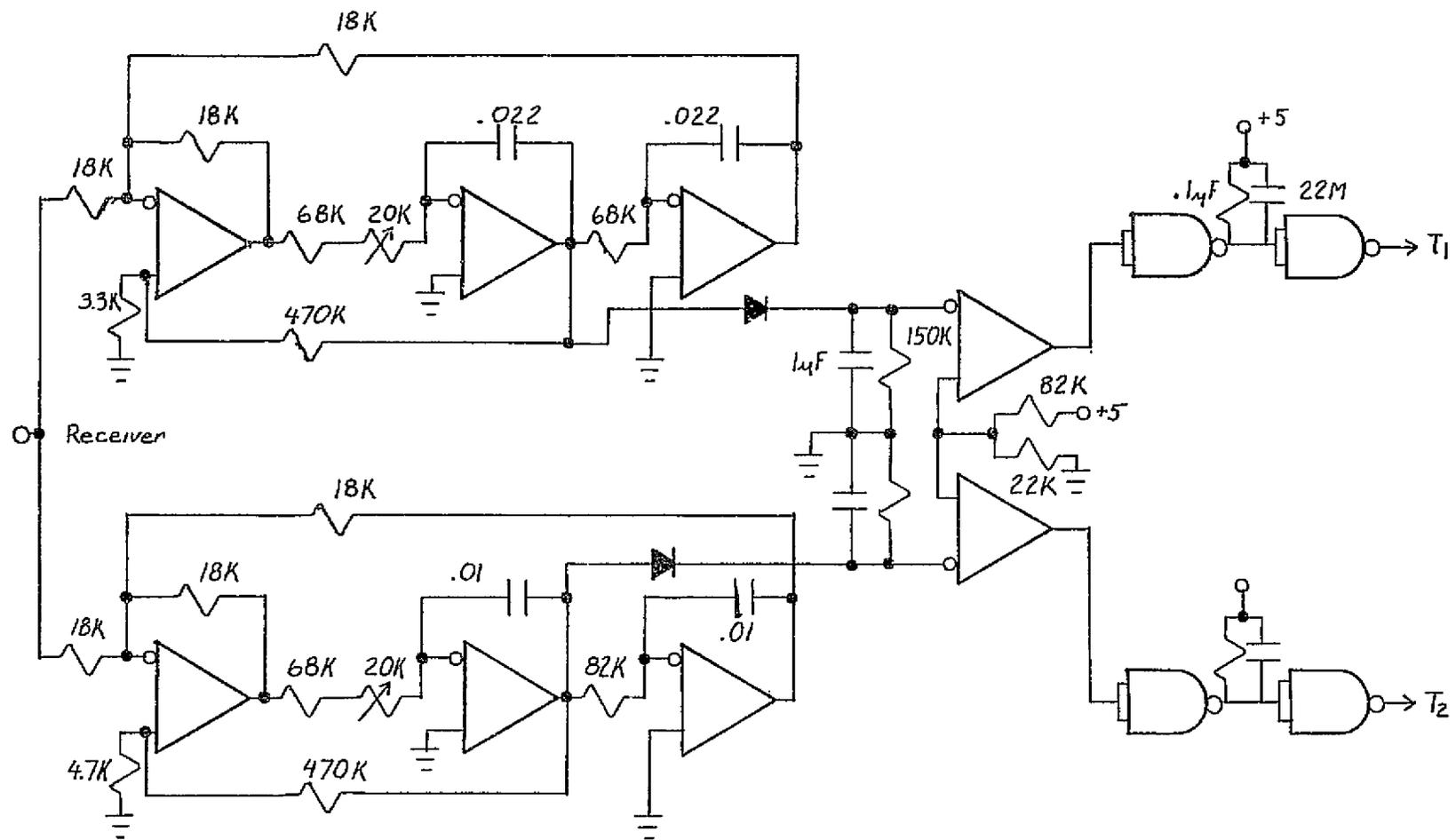
Figure 6. Tone Control

	INPUTS				PCM	
T1	T2	VOX	P_{rec}	P_{trans}	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
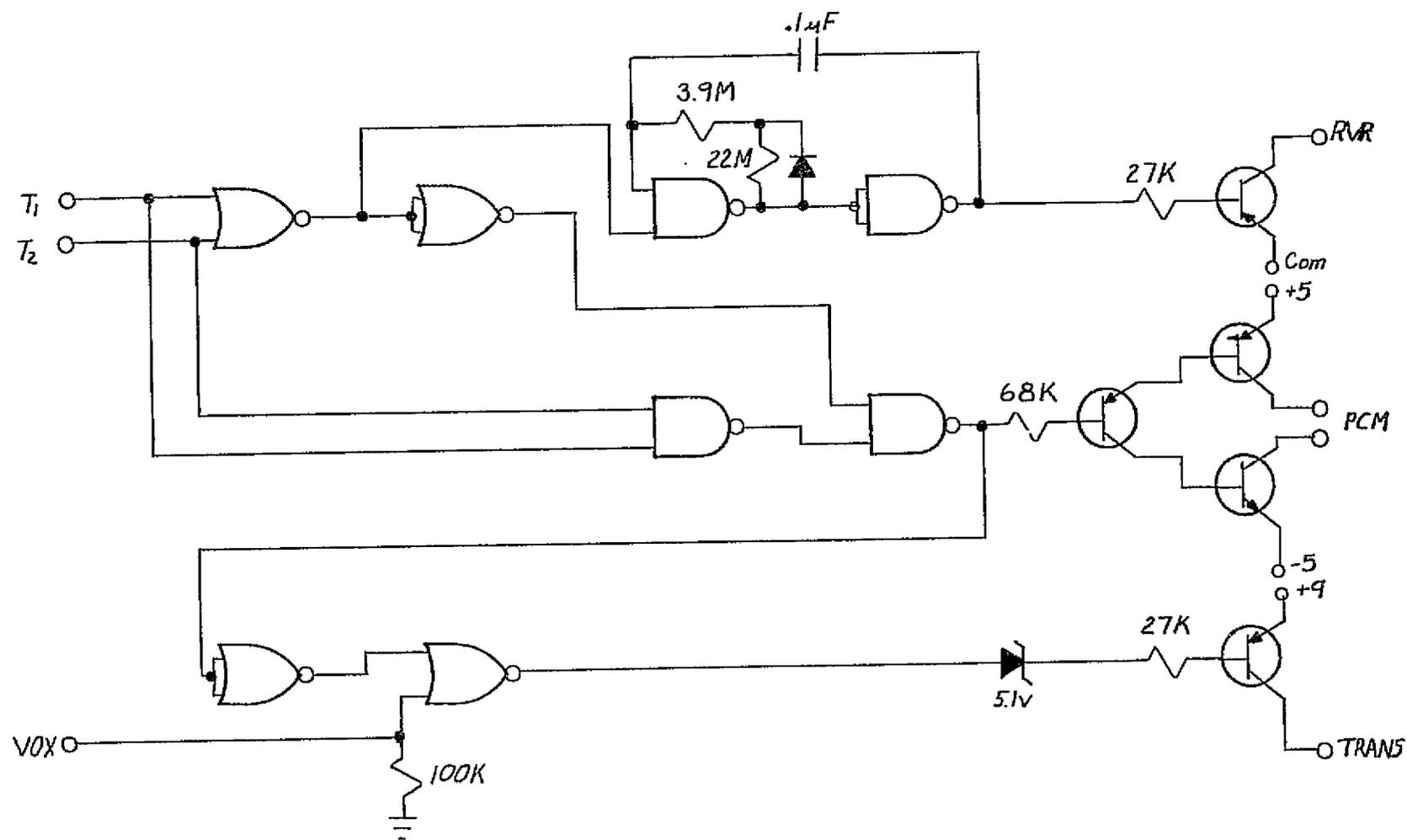
Figure 8. Transponder Logic and Power Control

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.
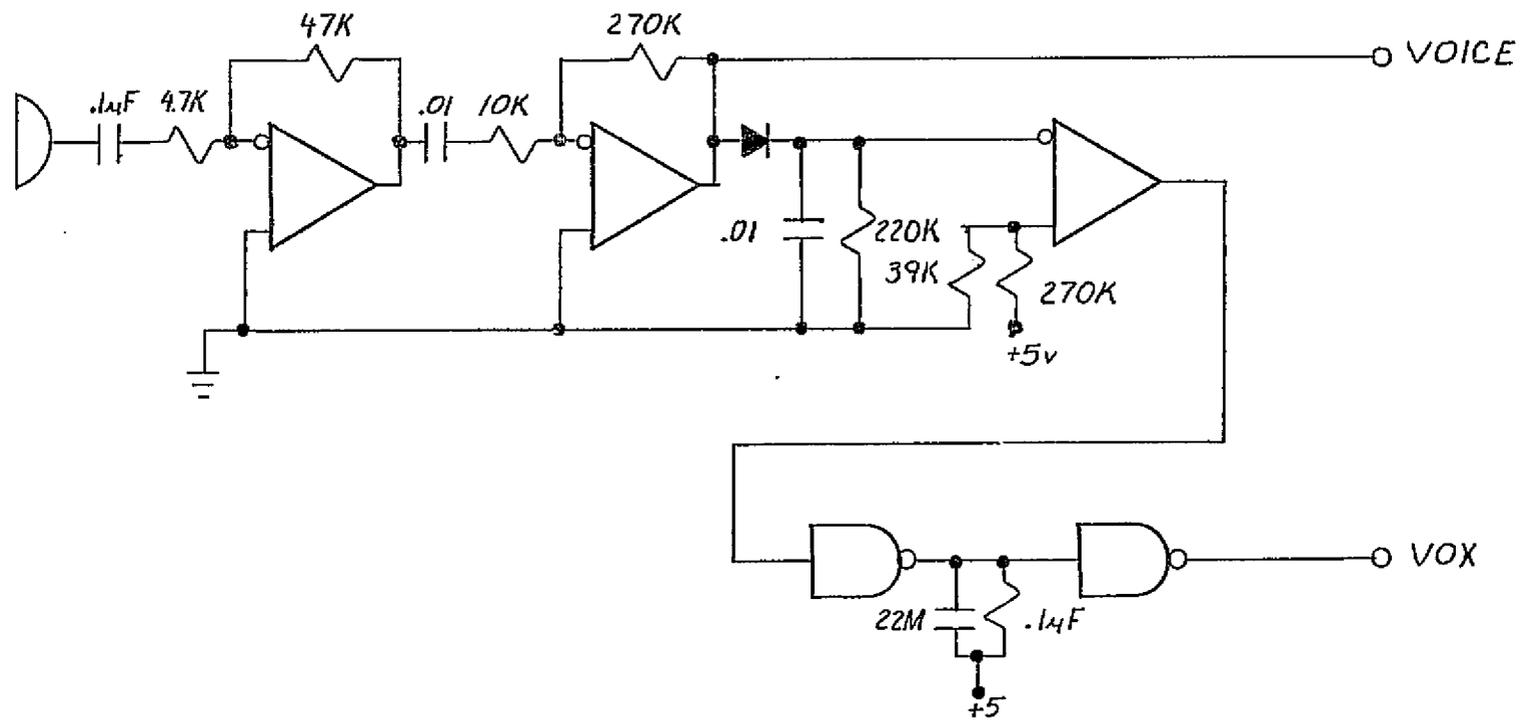
Figure 9.   Voice Amp and VOX
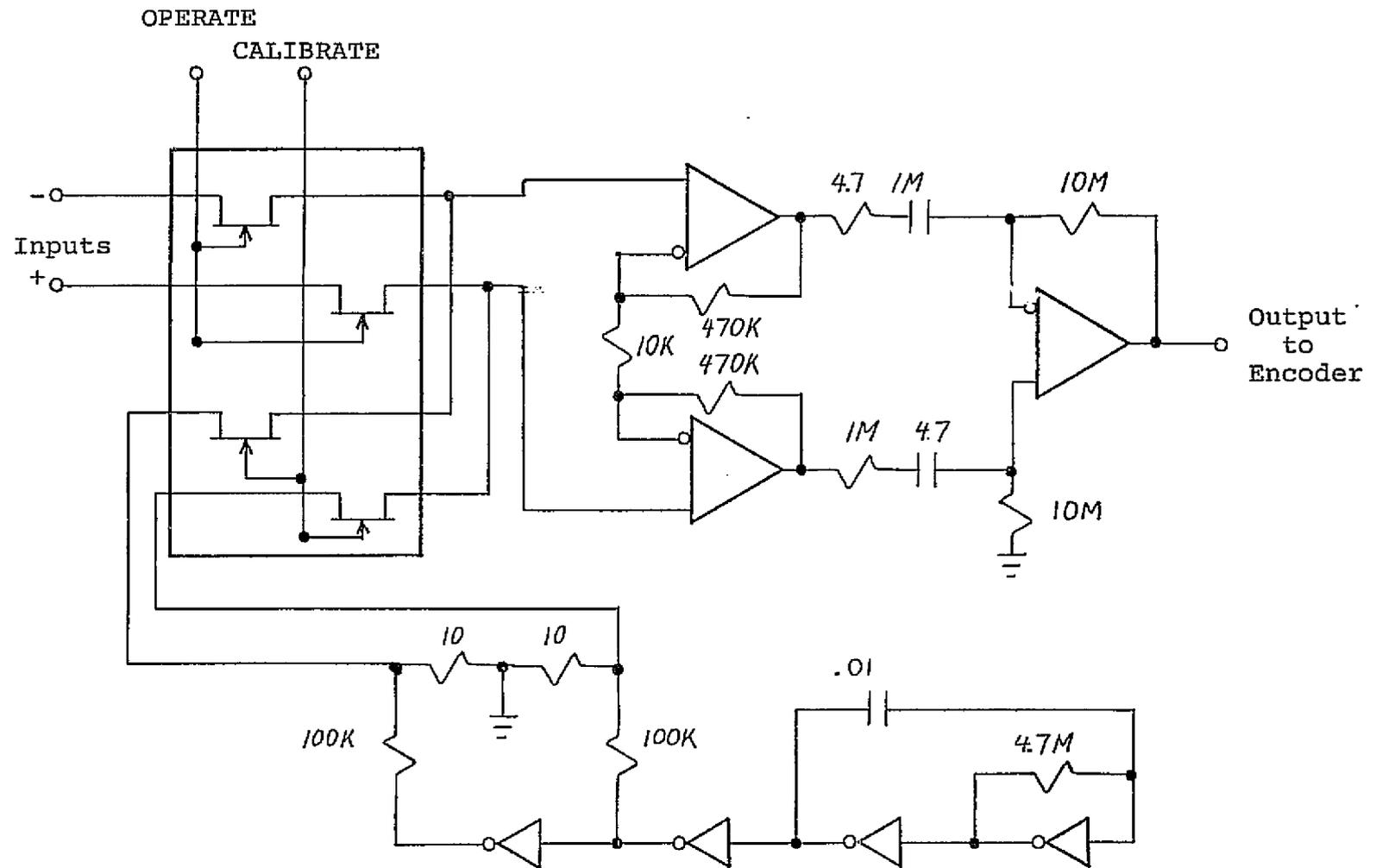
Figure 10. Signal Conditioners

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 µA.

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
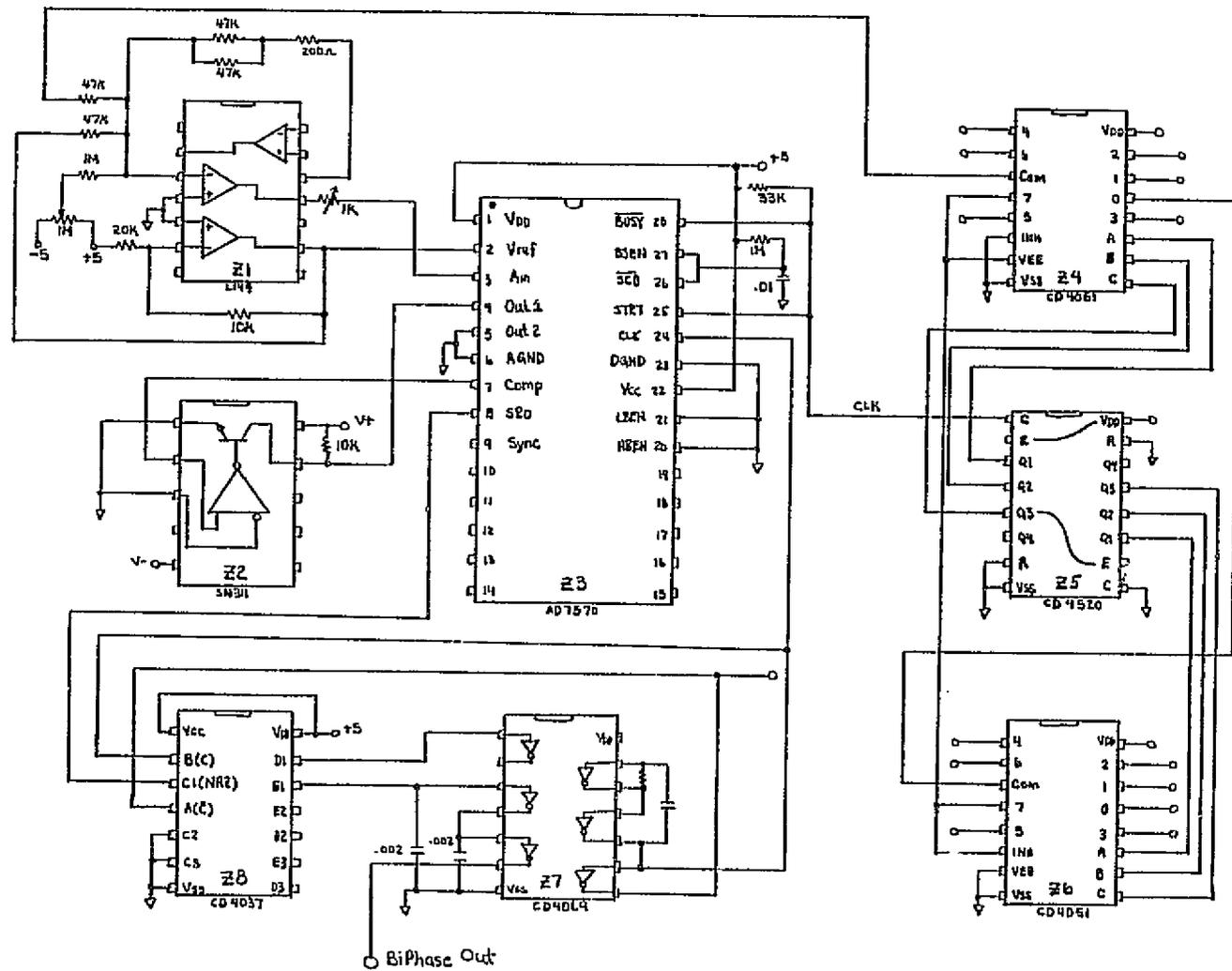
Figure 11.   PCM Encoder

between the time the last bit goes low and the end convers-
ion (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 contin-
uous 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 nega-
tive 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 design[5] 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-

a.

b.

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 earpiece 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 biphase 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
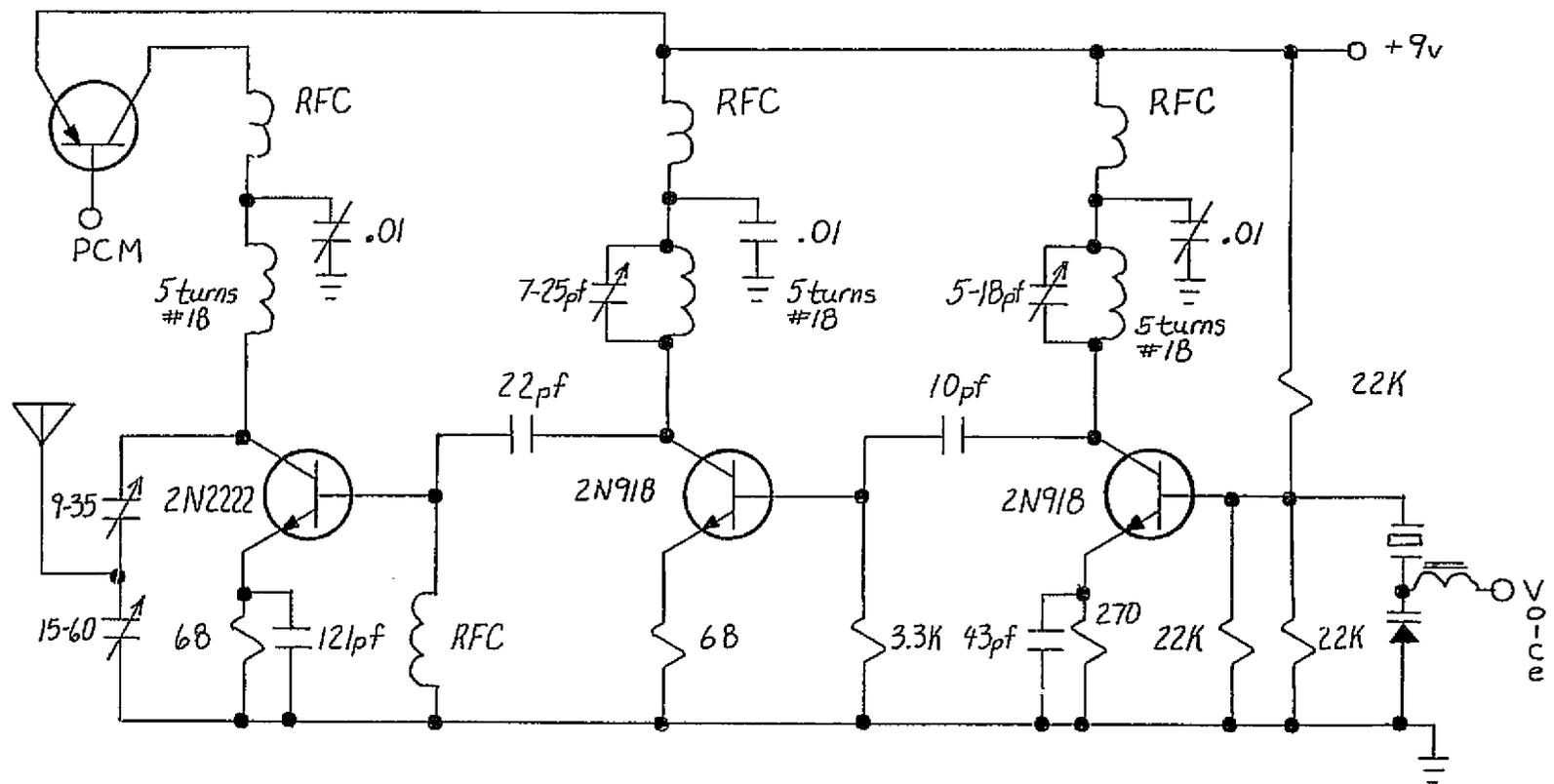
Figure 13.   Portable Transmitter
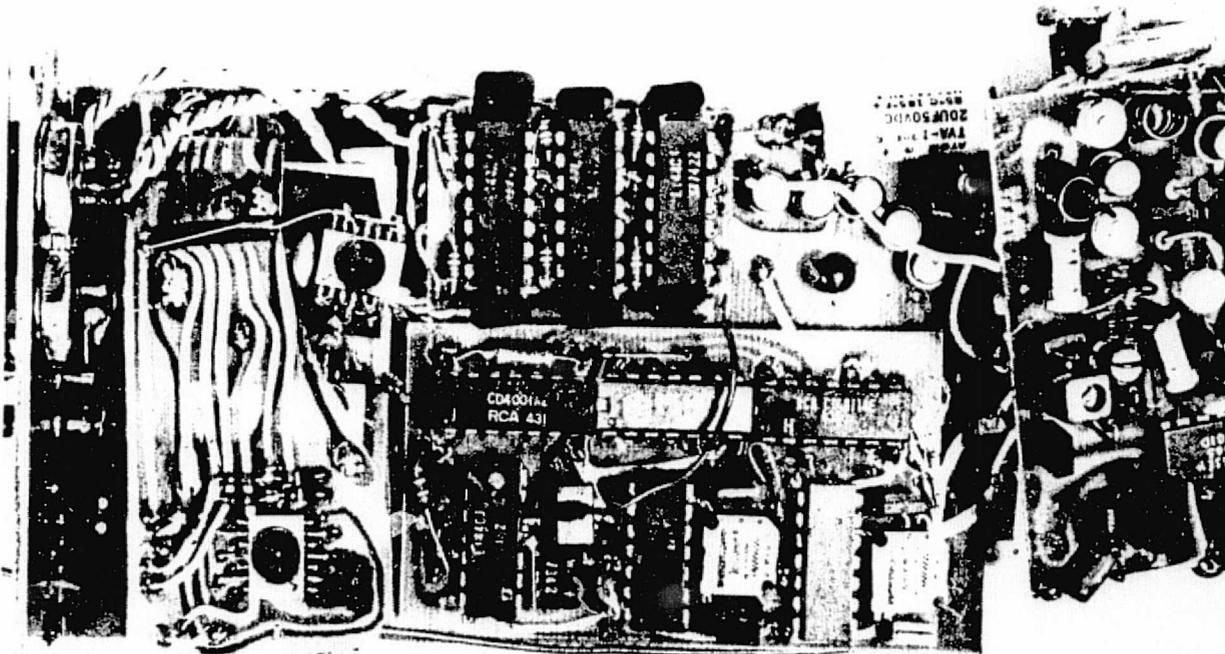
Figure 14. Detail of Circuit Board with Receiver Removed to Expose Transponder Circuit
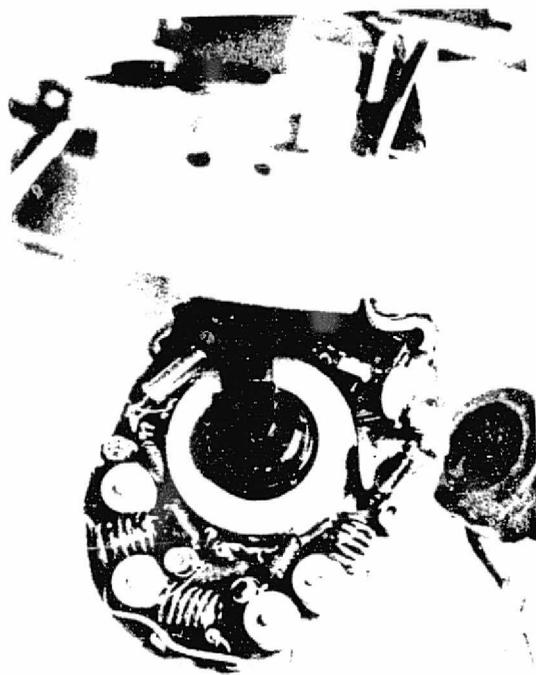
Figure 15.   Transmitter
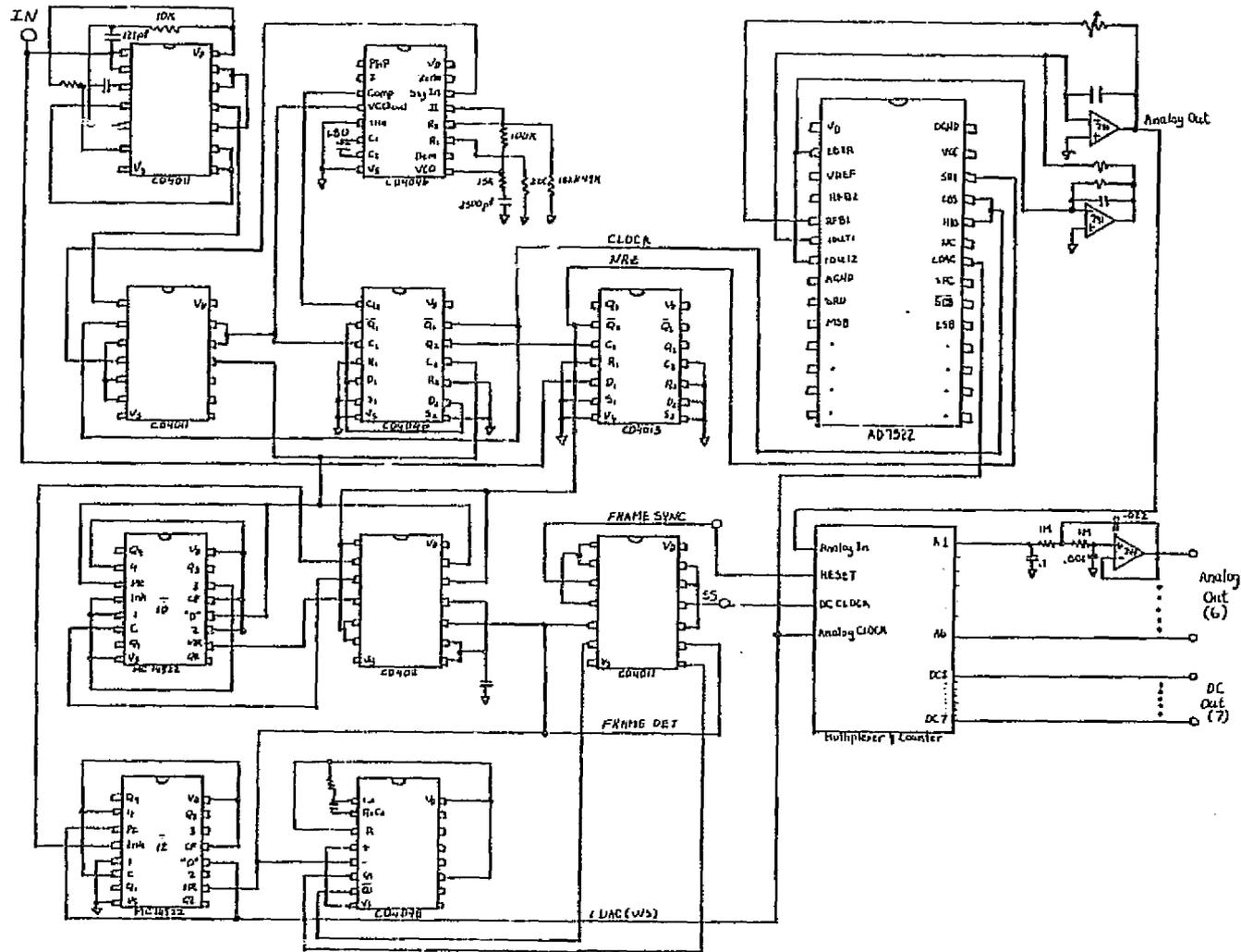
Figure 16. PCM Decoder

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 in-
verted 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 re-
covered 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 initi-
ally to synchronize the phase-locked loop; otherwise the
PLL may lock in on the wrong frequency. This is incon-
venient from a hardware point of view, because if the sig-
nal 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 possi-
bility of locking in on the wrong frequency. Lock-in
time, therefore, is within a few clock pulses, and con-
tinued 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.
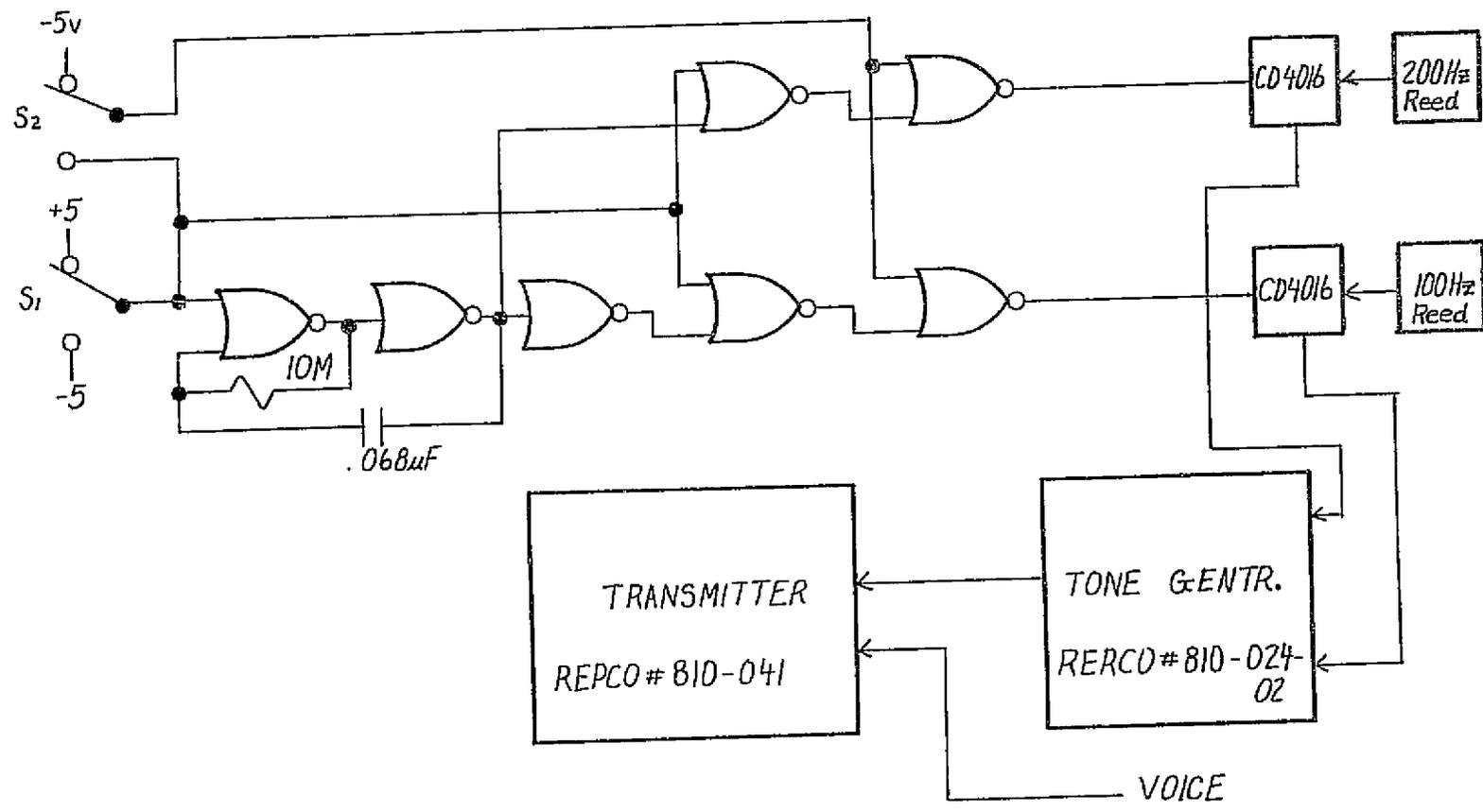
Figure 17.   GBS Tone Control

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
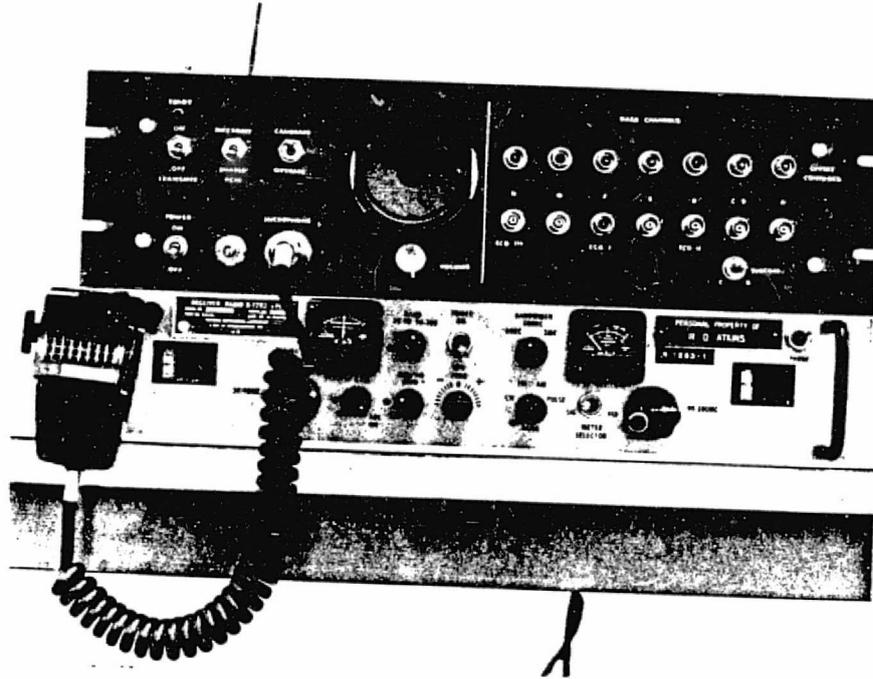
Figure 18.   Base Unit with Telemetry Receiver
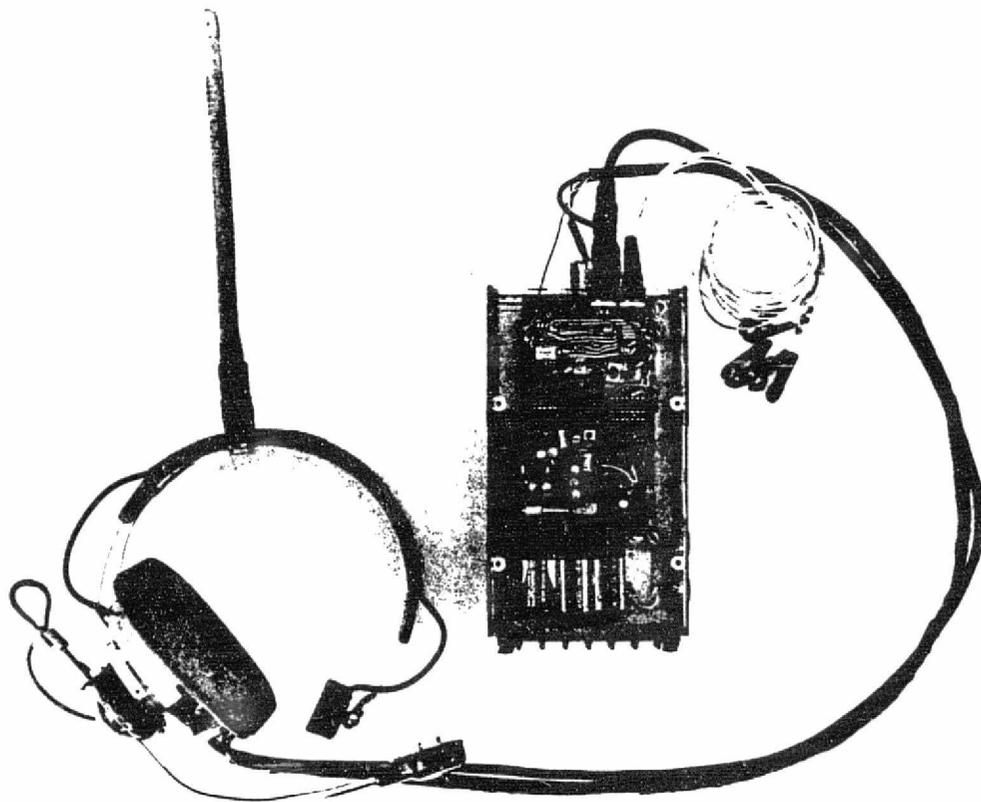
Figure 19. Portable Unit with Cover Removed

Figure 20.   Portable System in Use
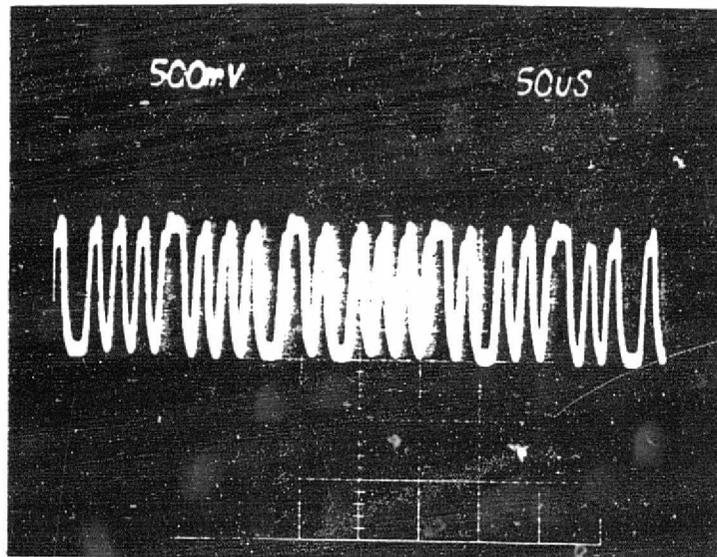
Figure 21.   Received PCM Data

Lead I

Lead II

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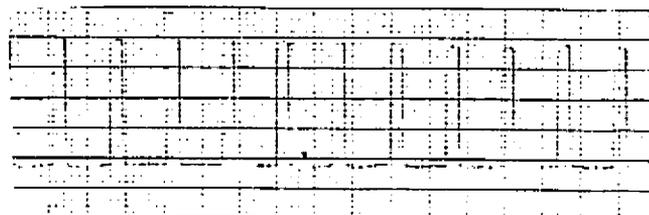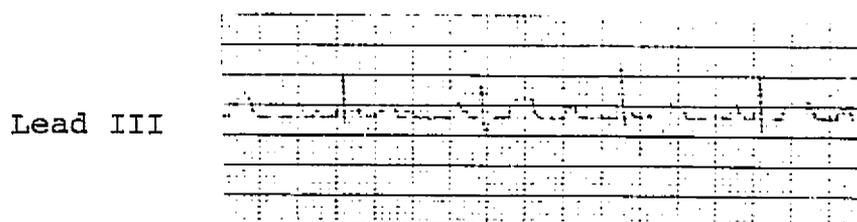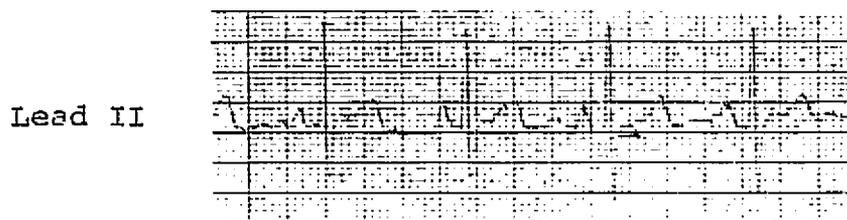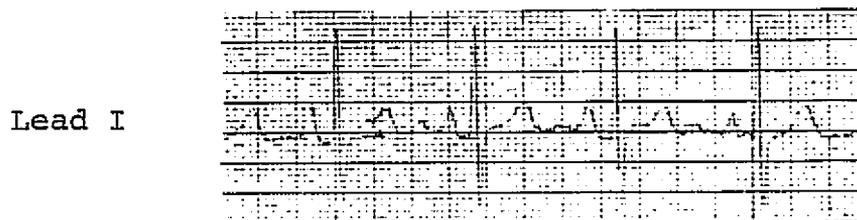
Calibrate signal present at the signal
conditioner inputs in the CALIBRATE
mode.   (The dashed line represents
voltage zero.)

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 dimen-
sions 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 tele-metry 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 com-munication. Ground base station has complete control of power to all subsystems in the portable unit. The major design problem in the previous NASA unit[5] (wideband, crystal controlled FM transmitter with tri-state logic) was addres-sed by using a crystal controlled AM transmitter and Man-chester 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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