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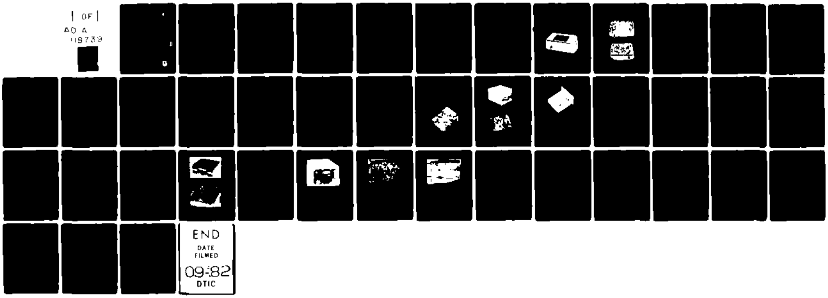

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Data Transmitters and Command Receiver Development

HANS LAPING

22 December 1981

AEROSPACE INSTRUMENTATION DIVISION PROJECT 7659
AIR FORCE GEOPHYSICS LABORATORY
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the development of a frequency-modulated VHF data transmitter, an HF frequency-shift keying low data rate transmitter and a dual-frequency HF command receiver. These units were designed for high altitude balloon control and data systems. An antenna for the data transmitter and a detector for FSK were also designed.

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Preface

The author wishes to thank Richard Ganion for his assistance in the development and testing of the equipment, and Catherine Rice for the many helpful suggestions during the writing of this report.

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Data Transmitters and Command Receiver Development

1. INTRODUCTION

This report describes the development of a very high frequency (VHF-40 MHz) narrow-band, frequency-modulated (FM) data transmitter, a frequency-shift keyed (FSK) high-frequency (HF) data transmitter, and a dual-frequency HF command receiver by the Balloon Instrumentation Branch of AFGL's Aerospace Instrumentation Division.

The primary purpose for developing these individual electronic modules was to update instrumentation for control of high altitude balloon payloads during medium and long duration balloon flights.

The dual-frequency receiver operates in conjunction with a command decoder, such as the BCS-18A Command Decoder-Selector, to control balloon payload functions up to several hundred miles away from our permanent balloon control center, located at Holloman AFB in New Mexico. The data transmitters provide the means to send the scientific data from the high altitude balloon payload to the permanent control center, or to an instrumented mobile van when balloon operations are required at remote locations, such as Alaska or Panama. Because of the narrow bandwidth limits imposed on the HF and VHF spectrum, both the transmitters and the receiver can be used only at relatively slow data rates.

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The chronological order of the development of each unit was dictated by the need to replace previously manufactured units. First, the LFMT-40A VHF narrow-band FM transmitter was designed, then the HF data transmitter, which was followed by a modification of an old command receiver and, finally, a new design of the command receiver. The units will be described in the order in which they were developed.

First, the LFMT-40A FM transmitter will be described in great detail. A somewhat briefer description of the HF-FSKT-1A transmitter (which is similar to the FM transmitter) follows. Finally, the development of the BCR-6A dual-frequency HF command receiver will be described.

2. LFMT-40A TRANSMITTER

The LFMT-40A transmitter was built on an old transmitter chassis originally manufactured by Zenith Radio Corporation under an Air Force contract. Externally, the LFMT-40A, shown in Figure 1, is identical to the BCT-3A Zenith transmitter.[1]

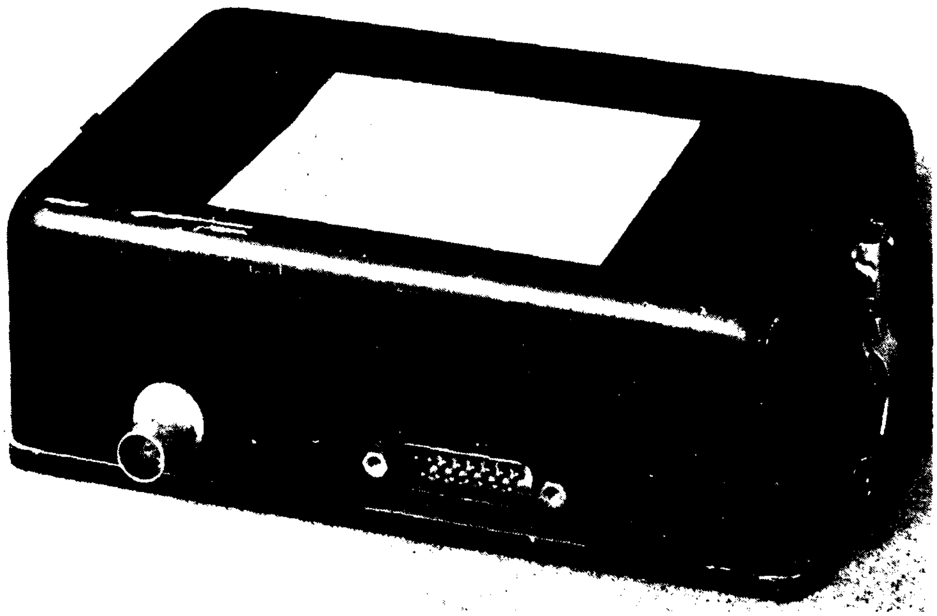

Figure 1. External View of LFMT-40A Transmitter

1. Zenith Radio Corporation (1966) Instruction Manual for BCT-3A Transmitter, Chicago, Illinois.

The BCT-3A transmitter, operated in the HF spectrum (4 MHz to 18 MHz), is suitable for carrier on-off keying. All components of the old Zenith transmitter were removed, and the new circuitry of the LFMT-40A narrow-band FM transmitter was built on the chassis as shown in Figures 2 and 3.

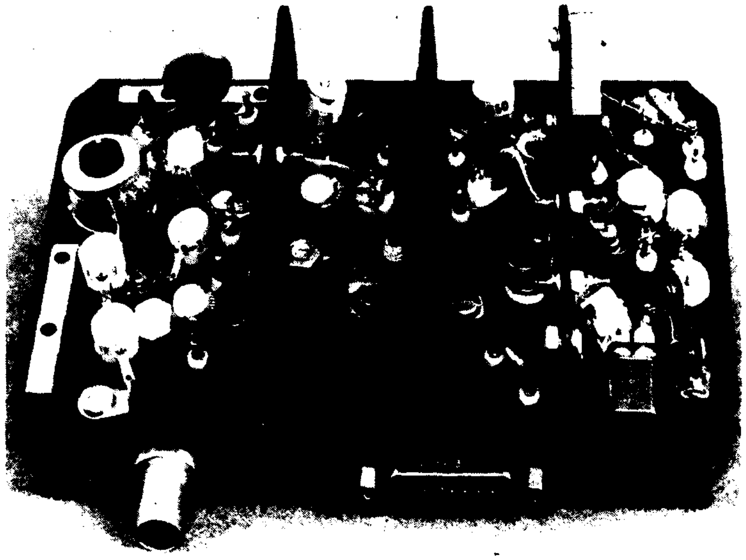

Figure 2. Internal View of LFMT-40A Transmitter (Top)

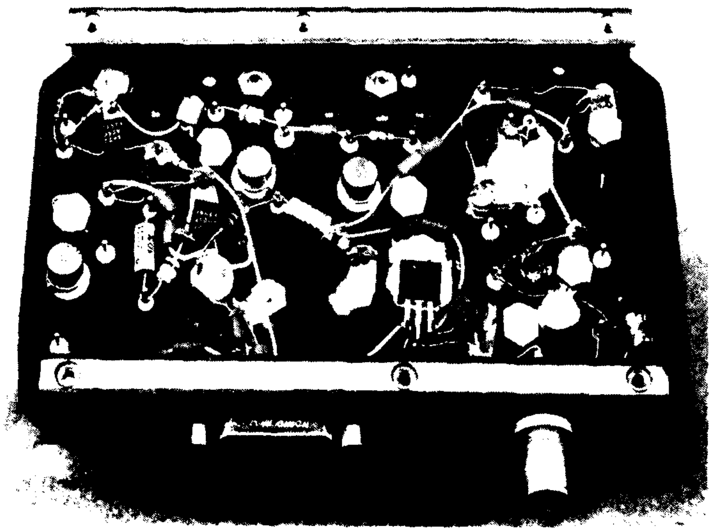

Figure 3. Internal View of LFMT-40A Transmitter (Bottom)

2.1 Background

In the early seventies, the Air Force inherited an air sampling program, sponsored by the Atomic Energy Commission (AEC) that utilized the VHF (40 MHz) spectrum for data transmission. Most equipment supplied by the AEC was outdated and unreliable due to numerous field modifications and constant use. The Air Force then contracted for a newer design for a 40 MHz transmitter. The new design proved to be unreliable and very sensitive to antenna mismatch, which caused spurious oscillation outside the authorized bandwidths. This became a problem for the Air Force's scientific balloon flights near White Sands Missile Range in New Mexico, where most of our ballooons are launched. Air Force Geophysics Laboratory (AFGL), therefore, decided to develop an inexpensive and reliable 40 MHz FM transmitter that can be used for those missions where low data rates (up to 3 kbits/sec) are acceptable.

Many balloon missions can be served with data rates this low or even lower, especially for passive or semi-passive experiments such as air sampling. The data rates are limited by the narrow bandwidths authorized in the VHF transmission spectrum. When higher data rates are required, IRIG-standard codes and transmission frequencies are available for the scientific balloon experiments.

2.2 Technical Specifications

The technical characteristics of the LFMT-40A FM transmitter are listed in Table 1. The unit is protected against reverse polarity and is current-limited.

2.3 Design Evolution

The design of this transmitter was changed several times before the final circuit was chosen. At first, the oscillator was built around a phase-locked loop (PLL) integrated circuit that proved to be very unstable and provided undesirable modulation characteristics. In the original design, the PLL oscillator was followed by a tuned buffer amplifier and tripler that fed a class A-B wide-band amplifier followed by a bipolar RF power transistor and a power matching circuit with a low-pass filter similar to the present circuit. The oscillator circuit was then changed to the present circuit of Q1 and its associated components. Because the wide-band amplifier had a low efficiency, it reduced the overall efficiency of the transmitter. It was replaced by the buffer amplifier Q2, and the driver amplifier Q3 that is a vertical enhancement mode metal oxide transistor (V-MOS), a fairly new device, with many superior characteristics such as high input impedance, good linearity, and stability.[2] Eventually, the final output transistor was also replaced

2. Siliconix, Incorporated (1978) VMOS Power FET's Design Catalog, Santa Clara, California.

Table 1. Technical Characteristics of LFMT-40A Transmitter

Frequency Range	38 MHz to 43 MHz
Frequency Stability	±.001%
Temperature Range	-30° to +60°C
RF Power Output	5 W
Emission Type	Frequency Modulation (16F3)
Power Supply Volts	+24 VDC ±4 VDC
Power Supply Current	500 mA
Audio Input Impedance (AC Coupled)	3000 Ohms
Audio Input Level at 3kHz for ± 3kHz Deviation	3 V peak to peak
Audio Distortion	5% at ±4 kHz deviation with 3 kHz modulation
Connectors	1 each BNC and 1 each DAM-15P
Spurious and Harmonic Attenuation	Greater than 60 db Below carrier
Weight	1 lb 6 oz
Size	6 in. x 4 in. x 2.5 in.
Duty Cycle	Continuous
Pressure Range	1 mb to 1000 mb

with a V-MOS RF power transistor for the same reasons given above. The V-MOS transistors have one great disadvantage; they are not quite as forgiving as bipolar transistors when used in high static environments. A few transistors were damaged by static electricity during breadboarding of the circuits when we changed many components that had to be soldered to the V-MOS output transistor.

2.4 Principles of Operation

Figure 4 shows the block diagram of the LFMT-40A transmitter. It operates in the VHF spectrum near 40 MHz and it employs frequency-modulation of the carrier.

A 20 VDC regulator provides constant voltage to the buffer amplifier, the driver amplifier, the final power amplifier, and the 12 VDC second voltage regulator. The 20 V regulator limits the current to the transmitter to about 1 A. If the transmitter gets too hot, due to continuous operation without a load or heat sink, an internal thermal overload protection circuit in the regulator that is mounted on the same metal surface as the final power transistor, limits the output current. The specifications for the 12 V regulator are similar to those

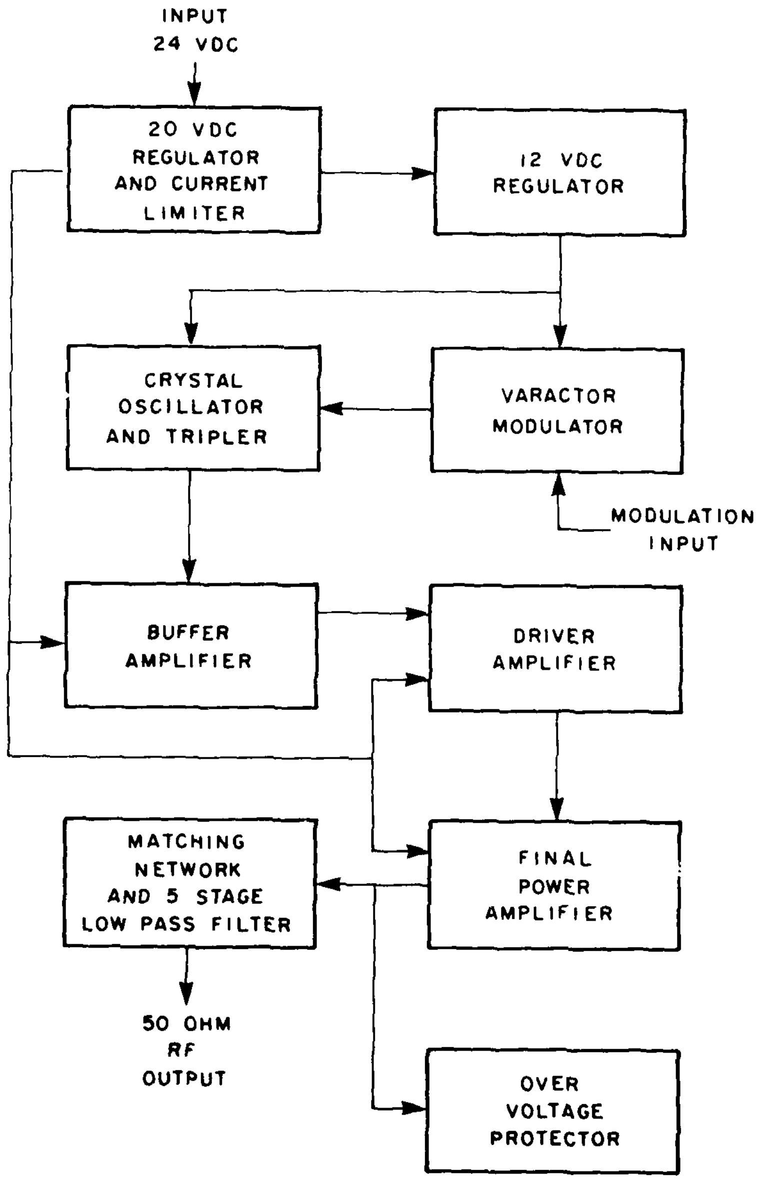

Figure 4. Block Diagram of LFMT-40A Transmitter

for the 20 V regulator, but the available current output is only about 100 mA. This regulator provides the power to the modulator and the crystal-controlled oscillator, the output of which is tuned to the third harmonic of the crystal frequency.

The tripled frequency of the oscillator is amplified by the buffer transistor, and filtered at the desired frequency. Additional power amplification and filtering is provided by the driver transistor, which, in turn, feeds the final power transistor. The final transistor is matched to a five-section, low-pass filter, the output of which provides a low harmonic distortion signal to a 50 ohm load or antenna.

The final output transistor is protected against overvoltage spikes due to output mismatches caused by open or short-circuited antennas that are possible during payload separation, at the end of a balloon mission, or during the recovery of the instrument package in the air or on the ground. This protection circuit was added after two aerial recoveries when we found that the output transistor shorted and failed.

Usually during aerial recovery of the balloon payload, the transmitting antenna is cut away, leaving a shorted coaxial cable as a load for the transmitter. This can create a reflected voltage higher than the breakdown voltage of the output transistor. After the overvoltage protection circuit was installed, recovery operations did not cause any damage to the output transistor.

This general description of the LFMT-40A transmitter could apply to many other transmitter designs. Later, when the HF-FSK-1A transmitter is described, many of the same comments will be applicable because, in principle, both designs are very similar. The description of the HF-FSK-1A transmitter, therefore, will contain much less detail.

2.5 Detailed Circuit Description

The circuits referred to in the following discussions are shown in Figure 5, which is a schematic diagram of the transmitter.

2.5.1 CRYSTAL OSCILLATOR

The crystal-controlled oscillator is a modified version of a Colpitts oscillator. A 12 V regulator supplies constant voltage to the oscillator (A2). This improves the stability of the oscillator when the input voltage to the transmitter is changed, and also maintains a constant power output level. Positive feedback on transistor (Q1) is achieved by C24 and C25. The crystal Y1 operates in its fundamental mode, which is one-third of the final output frequency of the transmitter. The tuned circuit of L4 and the varactor CR2 are used to fine-tune the crystal oscillator and also to frequency-modulate the transmitter. Changing the back bias across the varactor changes the capacity of the varactor which, in turn, varies the resonance of the crystal about its fundamental frequency. This causes a small change in the output frequency of the oscillator. The output of the oscillator is tuned to the third harmonic of the crystal frequency so that a frequency change due to the modulation voltage applied across the varactor diode is also tripled. Every varactor diode is tested before installation, to assure proper characteristics, because we found great differences between units. The ratio of R6 and R7 is selected so that a 4 V peak-to-peak audio signal causes a frequency deviation of ±4 kHz. This scheme provides good linearity and fairly low modulation distortion. The oscillator is biased so that the collector current is rich in harmonics. The oscillator operates best with a very low collector impedance; therefore, the output transformer is tapped at a low impedance point to provide low impedance at the fundamental frequency of the oscillator. Only the third harmonic is band-passed by the tuned circuit of L9 and C26. The voltage divider circuit of R1, R2, R3, and R4 provides the proper voltage to the varactor diode CR2 so that the transmitter will operate at the desired frequency. The resistor R4 is selected during the temperature compensation process of the oscillator. This can either be a fixed metal film resistor or a sensistor, which is a silicon resistor with a positive temperature coefficient. Every transmitter must be individually temperature compensated to maintain the required center frequency stability over the specified temperature range.

2.5.2 BUFFER AND DRIVER AMPLIFIERS

The output of the oscillator feeds the base of the buffer amplifier Q2 through C27. This signal contains a significant amount of the second harmonic frequency of the oscillator. The second harmonic is removed by the notch filter formed by L10 and C29 before the signal is amplified by Q2. The amplified output of the buffer is tuned and matched to the driver amplifier Q3. (Reference materials from RCA[3] and Motorola[4-6] were used in the design of the interstage and final output matching networks.) To improve stability and suppress spurious oscillations, a

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3. Minton, R., Design of Large-Signal VHF Transistor Power Amplifier, Radio Corporation of America, Publication No. ST-2665, Somerville, New Jersey.

4. Hejhall, R. C., A 160-MHz, 15-Watt Solid-State Power Amplifier AN-214, Motorola Semiconductor Products, Inc., Phoenix, Arizona.

5. Hejhall, R. C. A 50-Watt, 50-MHz Solid-State Transmitter AN-246, Motorola Semiconductor Products, Inc., Phoenix, Arizona.

6. Davis, F., Matching Network Designs with Computer Solutions AN-267, Motorola Semiconductor Products, Inc., Phoenix, Arizona.

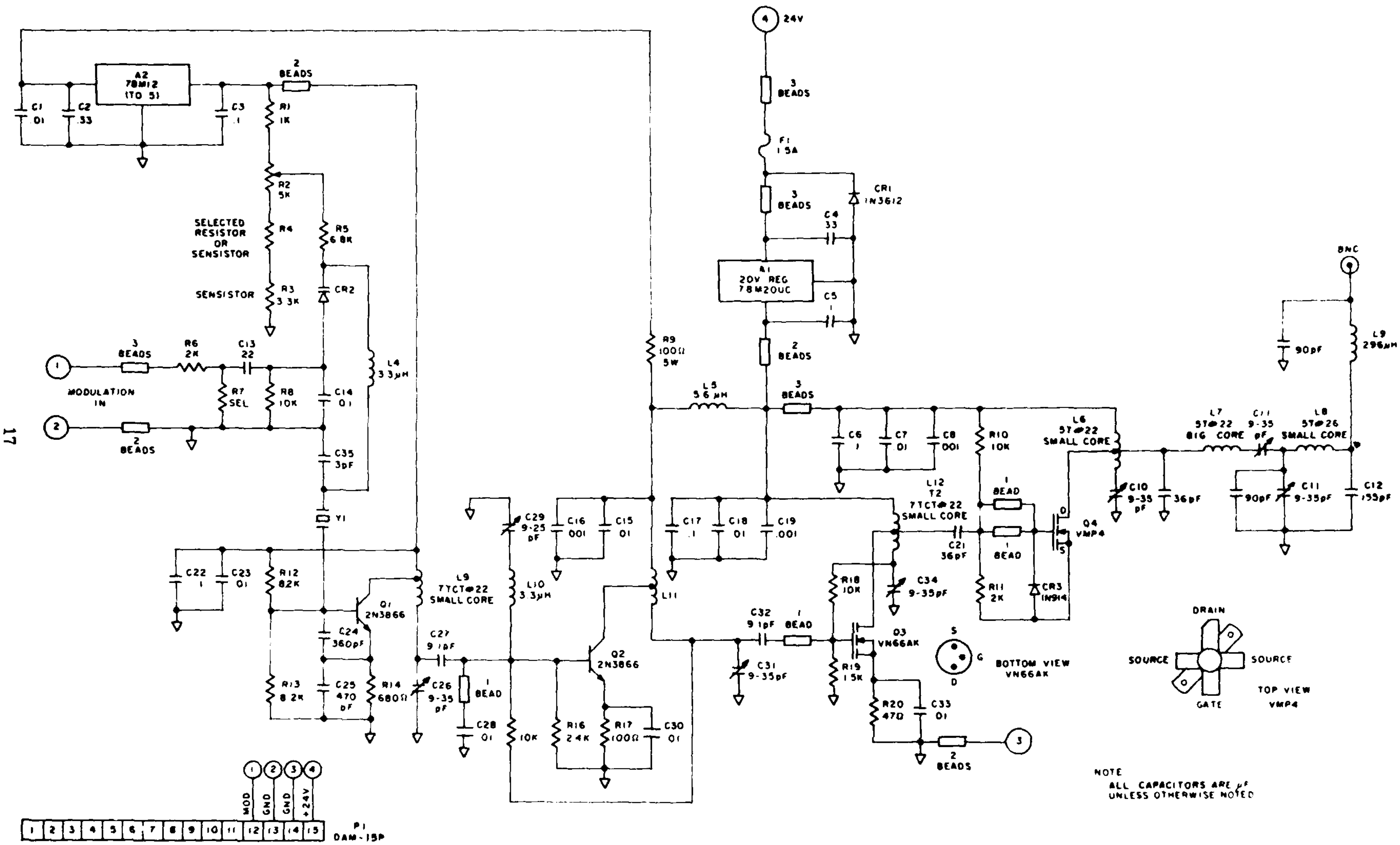

Figure 5. Schematic Diagram of LFMT-40A Transmitter

ferrite bead is used in the gate of the V-MOS driver amplifier Q3. The output of the driver amplifier is tuned and matched to the final amplifier Q4.

2.5.3 VOLTAGE REGULATOR AND INTERSTAGE FILTERING

The final output transistor Q4, the buffer, and the driver transistors are powered by a 20 V voltage regulator (A1) that feeds constant voltage to these stages, and simultaneously provides current-limiting and protection against high temperatures that could be caused by operating the transmitter without a load, or without an adequate heat sink. The efficiency of the transmitter would be somewhat greater if the 20 V regulator were not employed, but the improved stability and constant output power with variations of input voltage more than compensate for a small loss of efficiency.

Interstage isolation is achieved by low-pass filtering between stages. Each stage is bypassed by a parallel combination of several capacitors that are needed because not every capacitor provides a low impedance for all frequencies, even though the theoretical impedance would suggest that a 0.1 μf capacitor is a better bypass circuit than a 0.01 μf capacitor. In many instances, higher value capacitors actually become inductors and, therefore, are useless at higher frequencies. For this reason, several bypass capacitors are used in parallel at every amplifier stage. Inductors and ferrite beads are used for interstage decoupling. At this frequency (40 MHz), the beads have a definite advantage over a wire-wound choke because they provide an RF resistive loss without affecting the DC loss between stages, and the figure of merit (Q) is less than 1 over a wide frequency range, which is not true for RF chokes. RF chokes can become self-resonant (either series or parallel) at certain frequencies and, therefore, become ineffective as interstage decoupling devices at certain discrete frequencies.

All inductors employed in the tuned circuits are wire-wound, powdered iron toroidal coils that provide fairly high Q's. The Q is a ratio of inductive impedance to RF loss or resistance, and it determines insertion loss and bandwidth. Because toroidal coil forms concentrate the magnetic flux in the toroid, interstage radiation and coupling are minimized.

2.5.4 FINAL OUTPUT STAGE AND FILTERING

The final output transistor Q4 is biased near cutoff. A ferrite bead is inserted in the gate to increase stability and prevent spurious oscillation. A reverse-biased diode (CR3) is connected to the gate of Q4, which limits the negative input signal to about 0.7 V. This, in effect, keeps the breakdown voltage of Q4 at the rated value. High negative voltages on the gate of V-MOS transistors lower the drain-source breakdown voltage. The diode CR3, therefore, is an important component of the final amplifier circuit because the drain-source voltage is at maximum when the gate voltage is below about 0.8 V. The diode CR4 and the varistor V1 add additional protection to the output circuit of Q4. The varistor acts like a very high current Zener diode so that the output voltage of Q4 is limited to the breakdown voltage of the varistor V1. The type of varistor was chosen so that the minimum rated drain-source breakdown of Q4 can never be exceeded. This protects the transistor for all possible impedance mismatches.

The output resistance of Q4 is calculated as follows:

$$R_o = \frac{(Vd - Vsat)^2}{2P} \qquad \text{(from Ref. 2)}$$

where Vd - Supply Voltage

Vsat = Saturation voltage of Q4

P = desired output power

$$R_o = \frac{(20-1)^2}{2x6}$$

$$R_o = 30 \text{ ohms}$$

R_o and the parallel output capacity of Q4 is then matched to 50 ohms with the maximum power transfer circuit of L7, C9, and C11. The combination of L6 and C10 is used to cancel or tune out the output capacity of Q4. (Calculations of impedance matching are shown in Ref. 6.)

The impedance matching network is then cascaded with a 5-stage, 0.1 dB, Tchebycheff low-pass filter. This filter, and all other filters in this report, were designed according to Ref. 7; however, the Electrical Engineering Software Module of the TI 59 programmable calculator, manufactured by Texas Instruments, also provides a quick solution to low-pass filter problems.

The matching network, cascaded with the low-pass filter, provides a measured harmonic attenuation of more than 62 dB, which exceeds the required attenuation of:

$$AdB_{min} = -(43 \text{ dB} + 10 \log P)$$

where P = 5 W

$$AdB_{min} = -(43 + 6.99)\text{dB}$$

$$AdB_{min} = -49.99 \text{ dB}$$

A Tchebycheff low-pass filter was chosen over a Butterworth type because the Tchebycheff design provides more attenuation per octave than the Butterworth type.

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7. White Electromagnetics, Inc. (1963) A Handbook on Electrical Filters, Synthesis, Design and Applications, Rockville, Maryland.

2.6 Test Results

Ten LFMT-40A transmitters were built and used during a total of about 60 balloon flights with one failure, which turned out to be due to a cold solder joint in the output circuit. Even during this flight, acceptable data was received for a distance of 70 miles from our control center at Holloman AFB, NM.

3. 40 MHZ ZEPP ANTENNA

An antenna for the LFMT-40A transmitter was designed based on a tr[illegible] antenna first developed for Zeppelin airships.[8] The antenna is depicted in Figure 6.

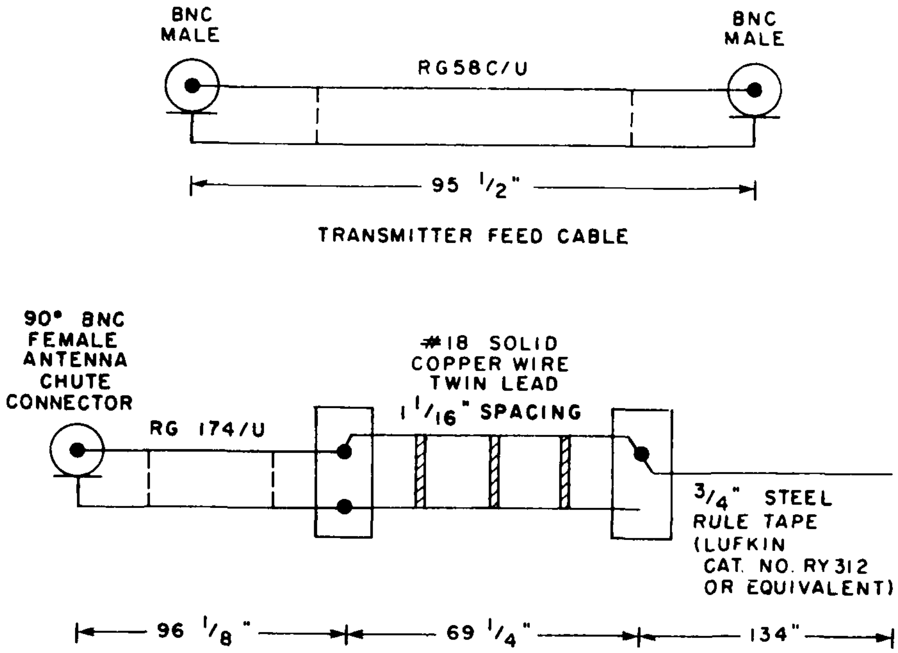

Figure 6. Diagram of 40 MHz Zepp Antenna

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8. American Radio Relay League (1980) The ARRL Antenna Book, Newington, Connecticut.

It consists of a half-wave radiating element followed by a quarte--wave twin-lead transmission line that feeds a half-wave coaxial cable. The characteristic impedance of the twin-lead line is 475 ohms, and the coaxial cable impedance is 50 ohms.

The input impedance Z_L of the radiating element is very high, and purely resistive. The twin-lead transmission line transforms this resistance to a lower resistance that is close to 50 ohms. The impedance transformation is as follows:

$$Z_s = \frac{Z^2{}_o}{Z_L}$$ (See Ref. 9, page 239)

The input impedance Z_L of the radiating element is a function of the length-to-diameter ratio;[10] the smaller the ratio, the lower the impedance. The exact length of every dimension of this antenna was verified experimentally with the use of a small tethered balloon, and the performance of this antenna in conjunction with the LFMT-40A transmitter was tested during several high-altitude balloon flights with excellent results.

Before balloon launch, the antenna is rolled up on a reel, and after launch it is released by a pyrotechnic device. The antenna then hangs vertically below the payload, generating an omni-directional radiation pattern in the horizontal plane. A half-wavelength RG174A/U cable is used to extend the distance from the payload to the radiating element. This cable stays flexible even at low temperatures; an RG58A/U cable does not. The feed line to the transmitter is always a multiple of a half-wavelength so that the resistive load impedance remains the same even if the impedance is not exactly 50 ohms. In fact, measurements of the antenna showed an input impedance of 45.6 ohms.

This type of transmitting antenna and deployment procedure have been successfully used for HF transmitters during the last twenty years. The input impedance of the Zepp antenna in the frequency range of 5-18 MHz is close to 20 ohms because the length-to-diameter ratio is much higher. The HF Zepp antenna is matched to 50 ohms with a wide-band transformer so that the length of the coaxial cable to the transmitter does not become critical. The deployable Zepp antenna for the HF spectrum was developed by Tufts University under an Air Force contract.

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9. Jordan, E. C. (1950) Electromagnetic Waves and Radiating Systems, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

10. Zenith Radio Corporation (1964) Handbook of Instruction for Dual-Frequency Command Receiver BCR-4A, Chicago, Illinois.

4. FSKT-1A TRANSMITTER

The HF FSKT-1A transmitter is similar to the LFMT-40A (40 MHz) transmitter described previously. Knowledge gained in the design of the 40 MHz transmitter was directly applied to the development of the HF transmitter, therefore, the description will include much less detail. Figure 7 shows the internal construction of the prototype FSKT-1A transmitter. Figure 8 shows the external view of the final transmitter model, and Figures 9 and 10 show the internal construction. [illegible] Heat-dissipating components of more than 0.5 W are mounted on the [illegible] chassis. Heat is transferred via the aluminum chassis to the front plate, attached to the case aluminum enclosure and the external heat sink. The [illegible] heat sink, with its four mounting nuts, is used to attach the transmitter to the aluminum flight instrumentation package.

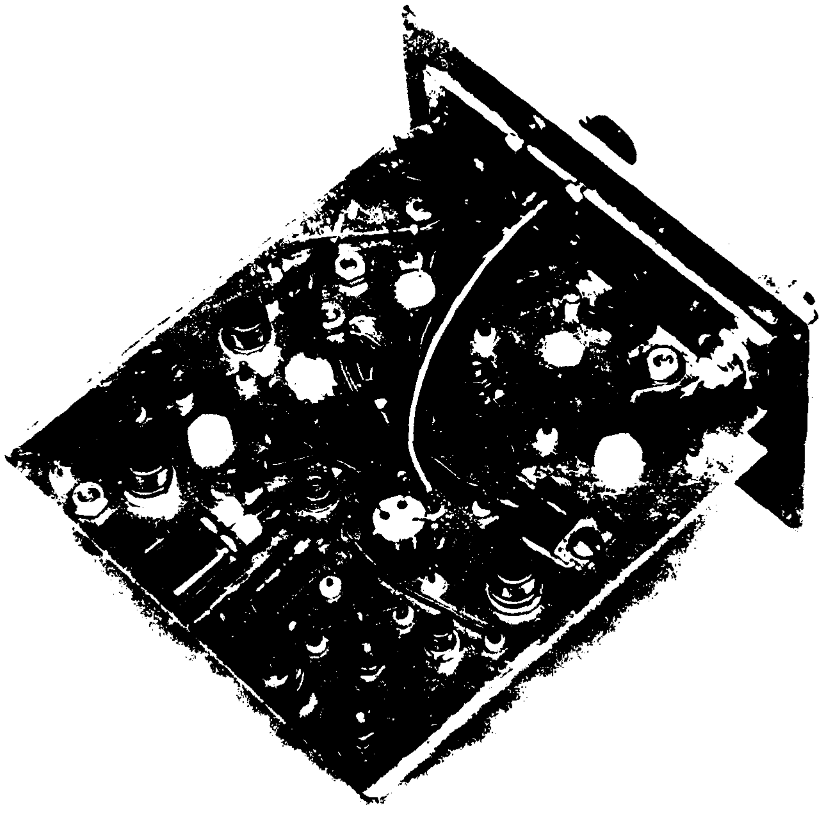

Figure 7. Prototype FSKT-1A Transmitter (Internal View)

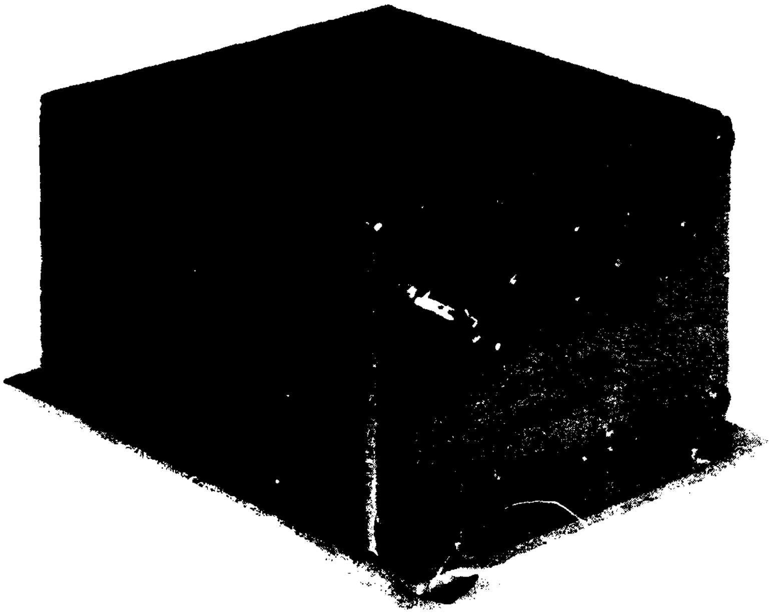

Figure 8. FSKT-1A Transmitter (External View)

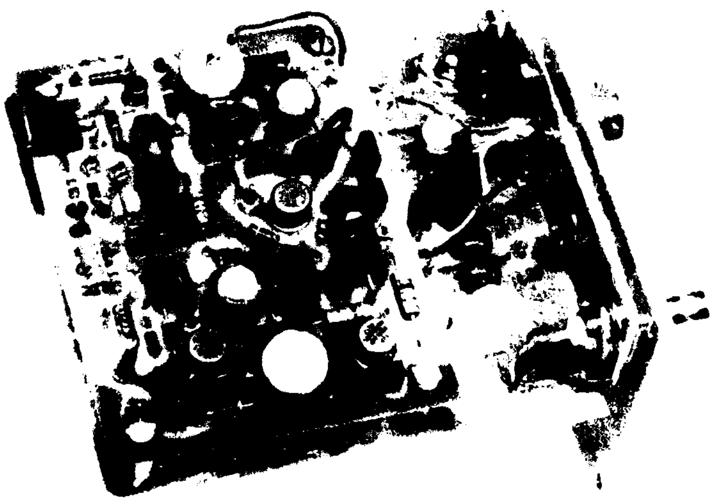

Figure 9. FSKT-1A Transmitter (Internal Top View)

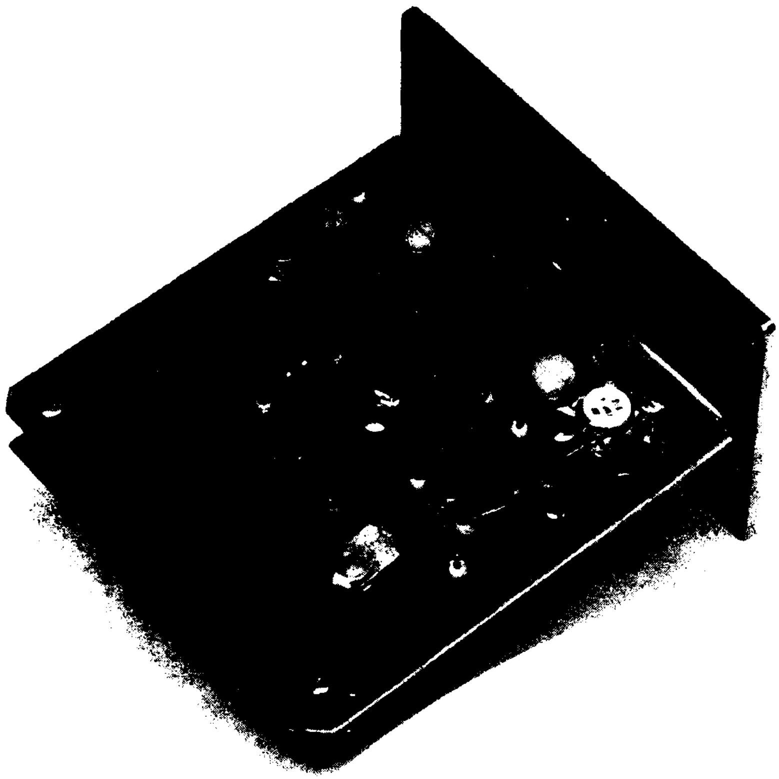

Figure 10. FSKT-1A Transmitter (Internal Bottom View)

4.1 Technical Specifications

The technical characteristics of the FSKT-1A transmitter are listed in Table 2. The unit is protected against reverse polarity, infinite voltage standing wave ratios (VSWR), and is current-limited.

4.2 Principles of Operation

The block diagram of the FSKT-1A transmitter is depicted in Figure 11. This diagram is almost identical to the block diagram for the LFMT-1A transmitter of Figure 4. Because the transistor gain in the HF spectrum is somewhat higher than in the VHF range, we were able to eliminate the buffer amplifier used in the LFMT-1A transmitter. This design employs a 20 V and a 12 V regulator. The 20 V regulator supplies power to the driver and final amplifier, and the 12 V regulator powers the crystal-controlled oscillator, the output frequency of which shifts

Table 2. Technical Characteristics of the FSKT-1A Transmitter

Frequency Range	4-18 MHz (fixed tuned)
Frequency Stability	± .002%
RF Output Power	8-10 W
Power Supply	24 V ± 4 V at 600 mA
Modulation (very narrow band FM) (very narrow band FM)	Frequency shift keying (ground closure shifts frequency high)
Connectors	1 each BNC (RF out) DEM-9P (Power and Modulation)
Pressure Range	1 mb to 1000 mb
Temperature Range	-30° to +60° C
Duty Cycle	100%
Spurious and Harmonic Attenuation	Greater than 60 dB
Weight	1 lb 12 oz
Size	2.75 in. (H) x 4.125 in. (W) x 4.5 in.

up and down according to the input code applied to the varactor frequency-shift keyer. The final output amplifier, matched to a fixed-tuned, 5-stage Tchebycheff low-pass filter, is protected against overvoltage (high VSWR). High-voltage spikes are detected and the resultant DC voltage is fed back to the driver amplifier, which reduces its gain and, therefore, reduces the input level to the final amplifier. This feedback arrangement is a design improvement not included in the LFMT-40A transmitter.

4.3 Detailed Circuit Description

Refer to the schematic diagram of the FSKT-1A transmitter in Figure 12.

4.3.1 CRYSTAL OSCILLATOR

The 12 V regulator A1 provides a constant voltage to the crystal oscillator consisting of Y1, Q2, and their associated components. The operating frequency of the oscillator is determined by the crystal Y1 and the series resonance of L3 and the capacity of the varactor diode CR1. Since the oscillator output shifts or deviates between two fixed frequencies, the bias established from R5 across the varactor CR1 determines the lower frequency of operation. A ground closure

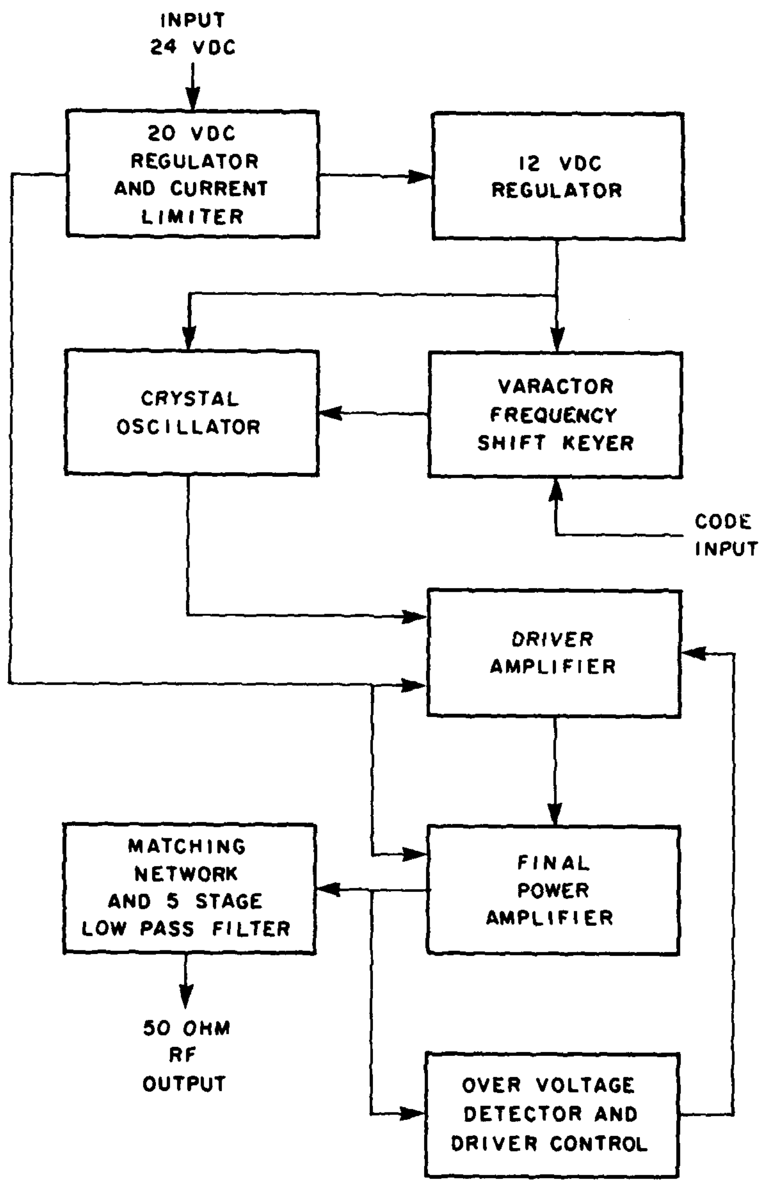

Figure 11. Block Diagram of FSKT-1A Transmitter

applied to R2 turns on transistor Q1, resulting in a higher bias voltage across the varactor CR1. This instantaneous increase in bias shifts the operating frequency to the upper value. The amount of frequency shift is determined by the value selected for R3. R8 is selected to frequency-compensate the transmitter oscillator. R8 can either be a fixed resistor or a sensistor. Other components without designated values are dependent on the operating frequency of the transmitter. The oscillator output is tuned to the fundamental frequency of the series-resonant crystal Y1, and then matched to the driver amplifier.

4.3.2 DRIVER AND FINAL POWER AMPLIFIER

The output from the oscillator is amplified by the driver transistor Q3, the output of which goes through a band-pass filter, and then is fed to the final output transistor Q5. The output matching network is calculated in the same manner as described in Ref. 6, and the low-pass output filter is calculated as shown in Ref. 7. Cutoff frequency is chosen at a value that is 10 percent higher than the operating frequency. The capacitors in the output matching network (C23, C24, C25) are variable capacitors during the tune-up procedure of the transmitter, and are later replaced by fixed capacitors having the required values.

4.3.3 DRIVER FEEDBACK CONTROL

If the transmitter is operated without a load, the voltage swing on the drain of Q5 could reach a value higher than the drain-to-source breakdown voltage. For this reason, the feedback circuit consisting of CR4, V1, and Q4 was included in the transmitter design.

The drain voltage swing of Q5 is peak-detected by diode CR4, and filtered by C26. Once the voltage across C26 reaches the breakdown voltage of the varistor V1, current flows through R18, and develops a forward gate voltage on Q4. Transistor Q4 starts to conduct, which increases the voltage drop across R12, resulting in a lower supply voltage for the driver amplifier Q3. This, in turn, lowers the power output capability of Q3, which provides the drive to the final amplifier. The net result of the feedback circuit is that during high VSWR conditions the circuit is activated, thus protecting the final output transistor, while under normal load conditions, the feedback circuit is deactivated and normal gain is achieved in the driver amplifier Q3. This feedback circuit is an important feature of the transmitter because the HF transmitting antenna is stored on a reel before balloon launch, causing a high voltage standing wave ratio.

5. FSK DETECTOR UNIT

The code received from the airborne transmitter is detected by a very narrow band discriminator that operates in conjunction with an ultra-stable frequency-synthesized HF receiver such as the RA 6790/GM receiver manufactured by RACAL, Inc. The IF output (455 kHz) from the receiver feeds the FSK detector. The schematic diagram, shown in Figure 13, includes two versions of an FSK detector. The basis of either design is the application of the PLL integrated circuit XR215 as a narrow band discriminator.

A1 uses two series resonant ceramic resonators, Y2 and Y3 at 455 kHz, as the center frequency control of the voltage-controlled oscillator (VCO). As the received frequency shifts about the center frequency of 455 kHz, the phase detector of the XR215 generates a small error signal that is amplified internally, and again externally, by the operational amplifier A2. The output of A2 turns Q2 on and off according to the received code. The output of Q2 is diode-coupled to a BNC connector that feeds a code converter where the data is displayed.

The second FSK detector consists of a balanced mixer A5, a crystal-controlled oscillator (Q1) at 13.6735 MHz, and a narrow band discriminator (A3). The IF frequency 455 kHz, and the oscillator frequency 13.6735 MHz, generate a difference frequency of 13.2185 MHz. The difference frequency is filtered and amplified by transistor Q3, the output of which feeds A3. The phase detector of A3, the VCO of which is crystal-controlled at 13.2185 MHz, generates an error signal corresponding to the input code which is then low-passed and amplified by A4. Operational amplifier A4 turns Q4 on and off according to the input code, which in turn, provides the input to a code converter. The numerical equivalence of the received code is then either printed, or displayed, and simultaneously recorded for future reference.

6. BCR-6A COMMAND RECEIVER

6.1 Background

The BCR-6A command receiver was designed to replace the BCR-4A command receiver originally made by Zenith Radio Corporation under an Air Force contract.[10] The BCR-4A receiver was the "workhorse" for high-altitude, long-duration balloon flights since the mid-sixties, but it had to be replaced because some components are no longer available for necessary repairs. The concept of a dual-frequency scanning receiver employed in the original Zenith command receiver was retained in the new design; however, the implementation was completely changed because newer and better components are now available.

6.2 Interim Solution

As an interim solution, many BCR-4A command receivers were completely modified by replacing the audio portion of the receiver, regulating the receiver DC operating voltage, re-biasing the RF and IF amplifiers, replacing all transistors, and changing the operating voltage from a negative supply to a positive supply with reverse polarity protection. Externally, the modified BCR-4A is identical to the original design shown in Figure 14.

Internally, all hand-wired components were replaced with a printed circuit board containing an automatic gain controlled (AGC) audio amplifier which was flight-tested first in the modi. d BCR-4A receiver. The modified receiver is shown in Figure 15.

More detail will be given later in the BCR-6A description. (This same audio AGC circuit was also successfully employed in a VHF (140 MHz) narrow-band FM command receiver[11] that can be utilized for line-of-sight balloon control.)

6.3 Technical Specifications

The technical characteristics of the Dual-Frequency Command Receiver are listed in Table 3. The unit is voltage-regulated at 12 V, current-limited, and protected against reverse polarity.

6.4 General Description

The new BCR-6A receiver consists of two printed circuit boards mounted on a chassis enclosed by an aluminum case as shown in Figure 16. The RF amplifiers, the crystal-controlled oscillators, the mixers, and the first IF circuits are located on a printed circuit board depicted in Figure 17. The circuit board of the second IF and the audio section are displayed in Figure 18.

6.5 Principles of Operation

Refer to the block diagram of the BCR-6A receiver shown in Figure 19. The timer-frequency selector continuously scans two fixed RF frequencies by alternately energizing the mixer and oscillator of each corresponding RF input section at a rate of twice per second. This scanning action occurs until an RF signal with the proper modulation or intelligence is received, amplified, and decoded by an associated command decoder such as the BCS-18A.[12] At that moment, a feedback

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11. Laping, H. (1981) Development of a Low Data Rate Repeater, AFGL-TR-81-0019, ADA108154.

12. Laping, H. (1980) BCS-18A Command Decoder-Selector, AFGL-TR-80-0249, ADA099384.

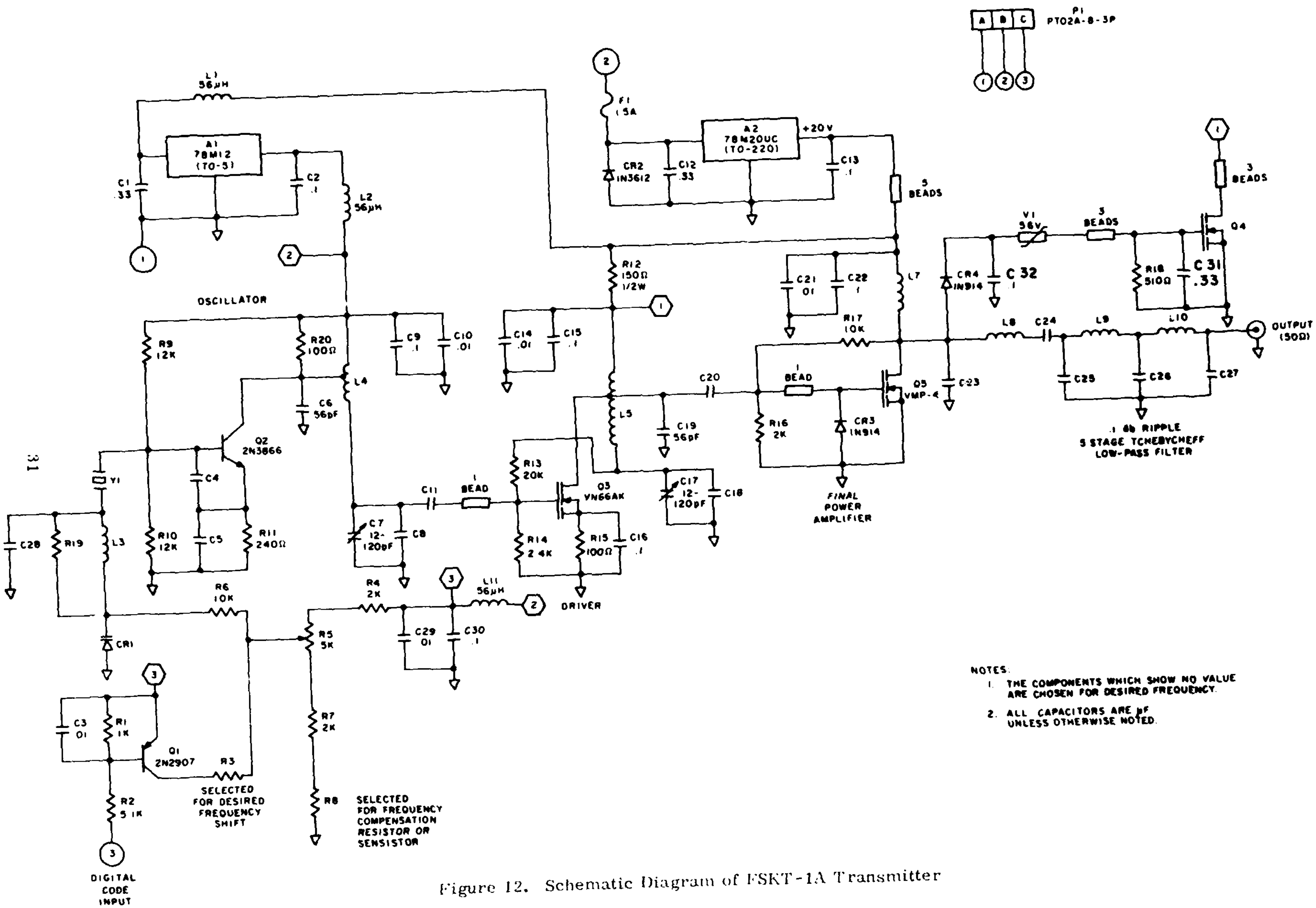

Figure 12. Schematic Diagram of FSKT-1A Transmitter

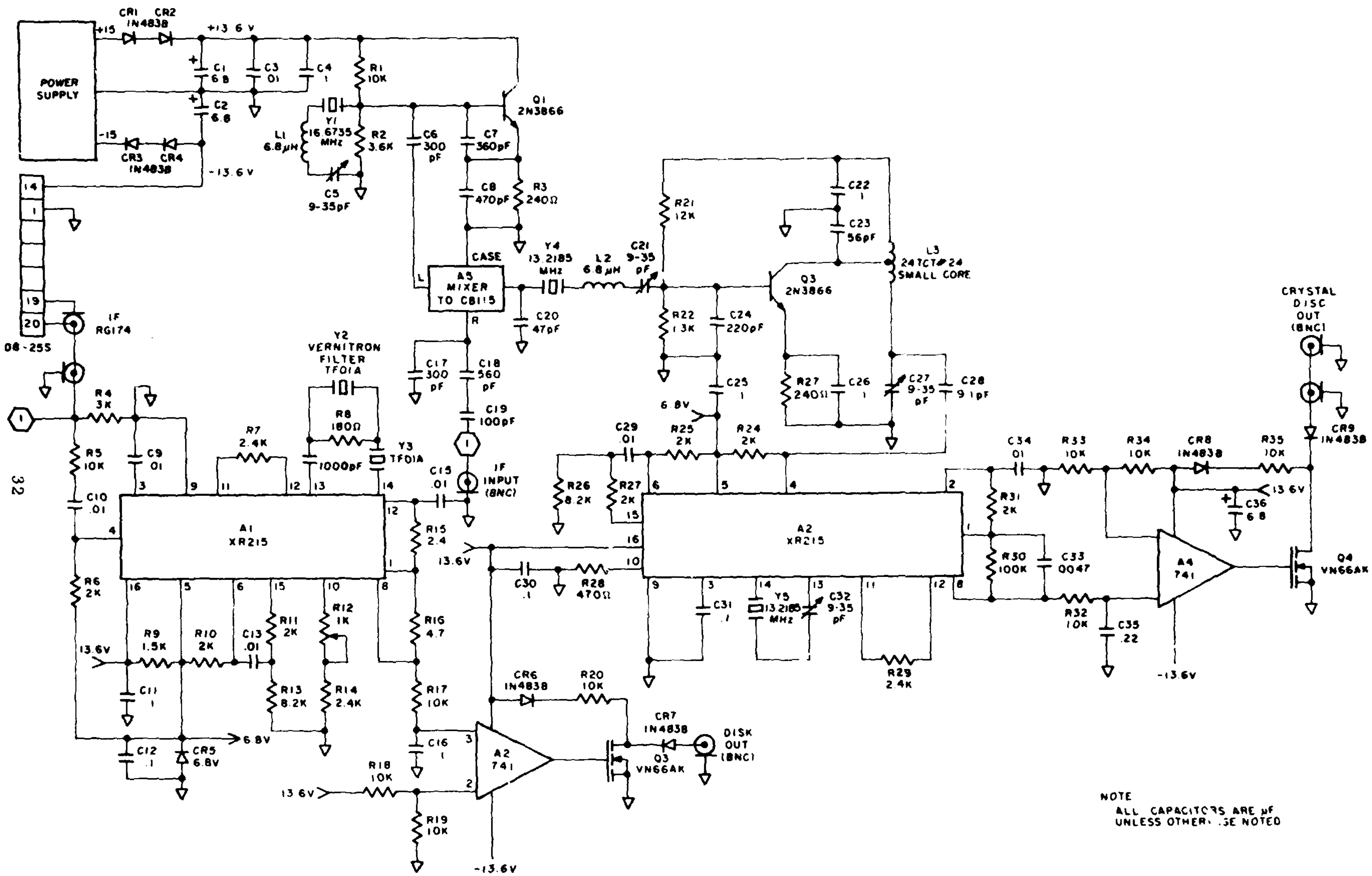

Figure 13. Schematic of FSK Detector Unit

NOTE
ALL CAPACITORS ARE μF UNLESS OTHERWISE NOTED

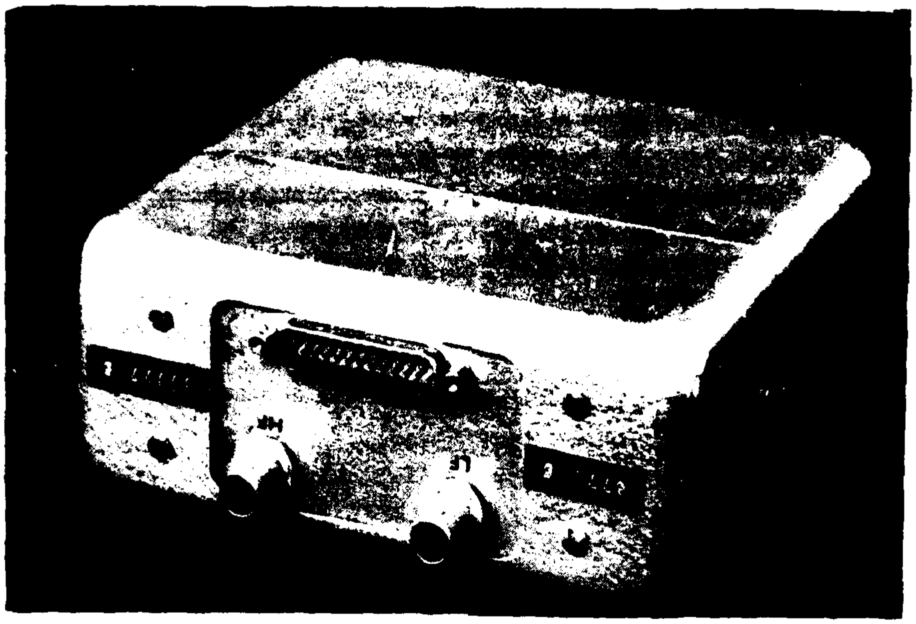

Figure 14. BCR-4A Modified Command Receiver (External View)

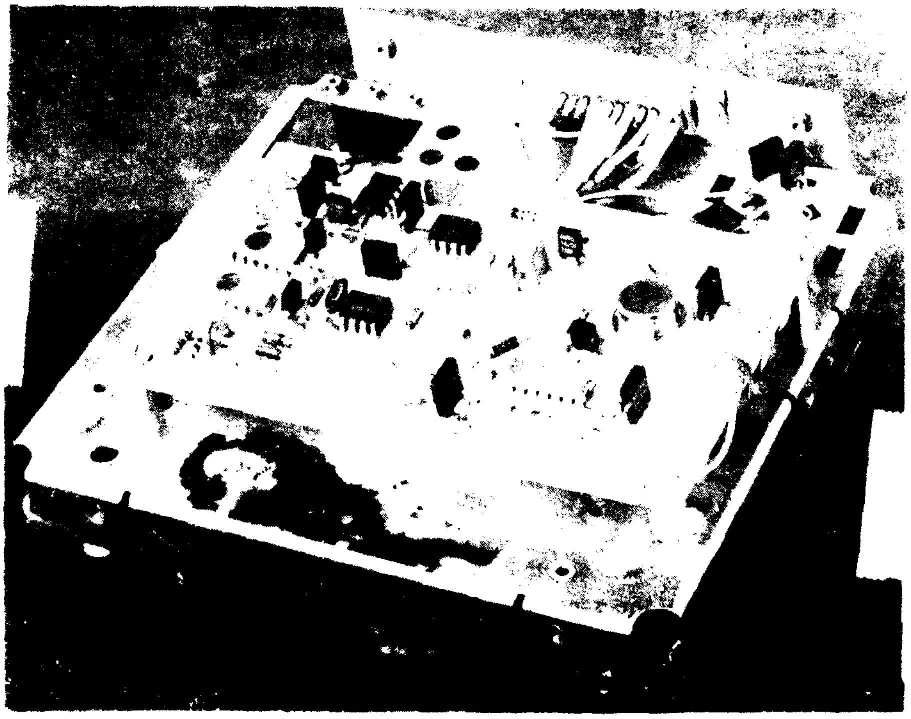

Figure 15. Modified BCR-4A Receiver (Internal Modification)

Table 3. Technical Characteristics of BCR-6A Receiver
(Average Values)

Frequency Range	4-18 MHz (fixed crystal controlled)
Type of Reception	Amplitude Modulation
Sensitivity	.6μ V for 10 dB $\frac{S+N}{N}$ ratio
Second IF Selectivity (55 kHz)	4 kHz at 3 dB point 11 kHz at 60 dB point
First IF Selectivity (21.4 MHz)	13 kHz at 6 dB point ± 7.5 kHz at 60 dB point ±22.5 kHz at 80 dB point ultimate attenuation 100 dB
Image Rejection	75 dB or greater
Audio Output Voltage	1 Vrms into 55 ohm load
Automatic Gain Control	Less than 1 dB change with RF signal input of 1.5 to 100,000 μ V
RF Input Impedance	50 ohms, unbalanced
Operating Temperature	-30° C to +60° C
Operating Pressure	1 mb to 1050 mb
Power Requirements	14 Vdc to 28 Vdc at 60 mA
Connectors	2 BNC for antenna lead-ins one 9 pin (DE-9P) for power inputs and control outputs
Weight	2 lb 4 oz
Dimensions	6-1/8 in. x 4-1/8 in. x 2-3/4 in.

signal from the decoder provides an input signal to the frequency selector which, in turn, locks on to the RF section with the proper intelligence. Once the intelligence (proper modulation) of the RF signal is removed, the scanning action is then reinitiated; therefore, the presence of an RF signal alone does not cause the receiver to lock to a signal as is the case with many scanning receivers. Each frequency can also be selected by an external input during testing, or when only single-frequency reception is desirable.

The following discussion assumes that only one frequency is selected, because the comments for the second frequency would just be repetitive.

The antenna feeds a 3-pole band-pass filter, the output of which drives the RF amplifier. Signals from the RF amplifier and the crystal-controlled oscillator are combined in the mixer that generates the first IF signal of 21.4 MHz.

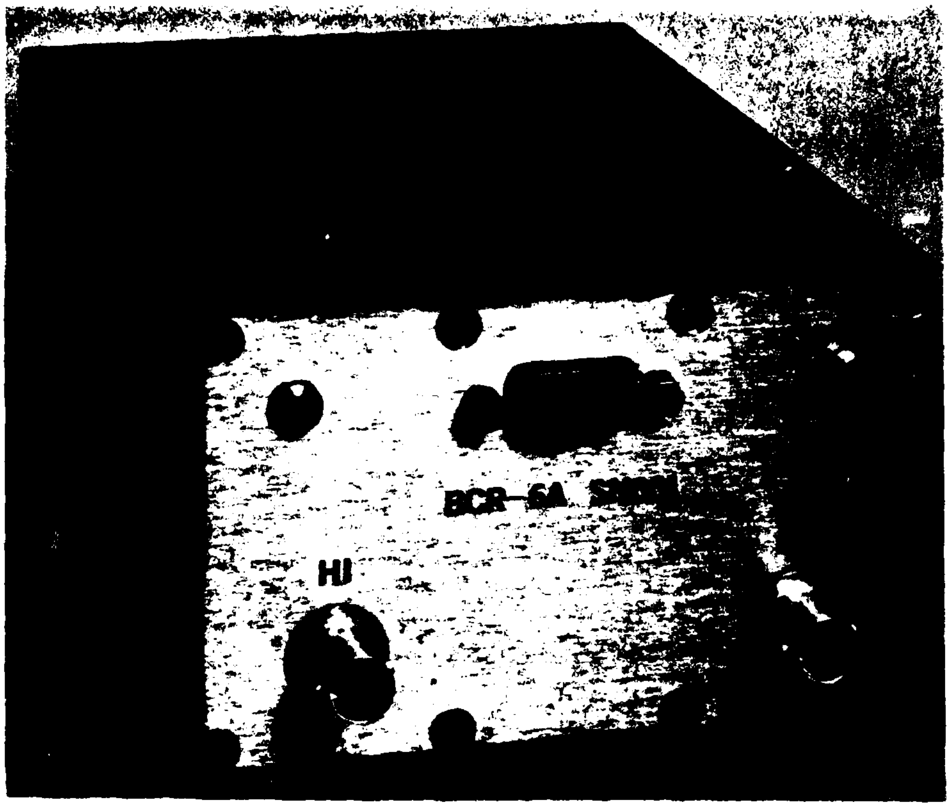

Figure 16. BCR-6A Receiver (External View)

This frequency is band-passed by a crystal filter, the output of which combines in the second mixer with a crystal-controlled oscillator signal resulting in a second IF signal of 455 kHz. This signal is amplified, band-passed by a very narrow ceramic filter, and detected. The detected signal from the original amplitude-modulated carrier feeds an audio amplifier that has an AGC circuit to provide a relatively constant output signal to a command decoder. Outputs from the command decoder control the final remote functions in the high-altitude balloon payload. Because this receiver operates in the high-frequency spectrum, remote functions can be activated several hundred miles from the control station.

6.6 Detailed Circuit Description

Refer to the schematic diagram of the RF circuit board shown in Figure 20.

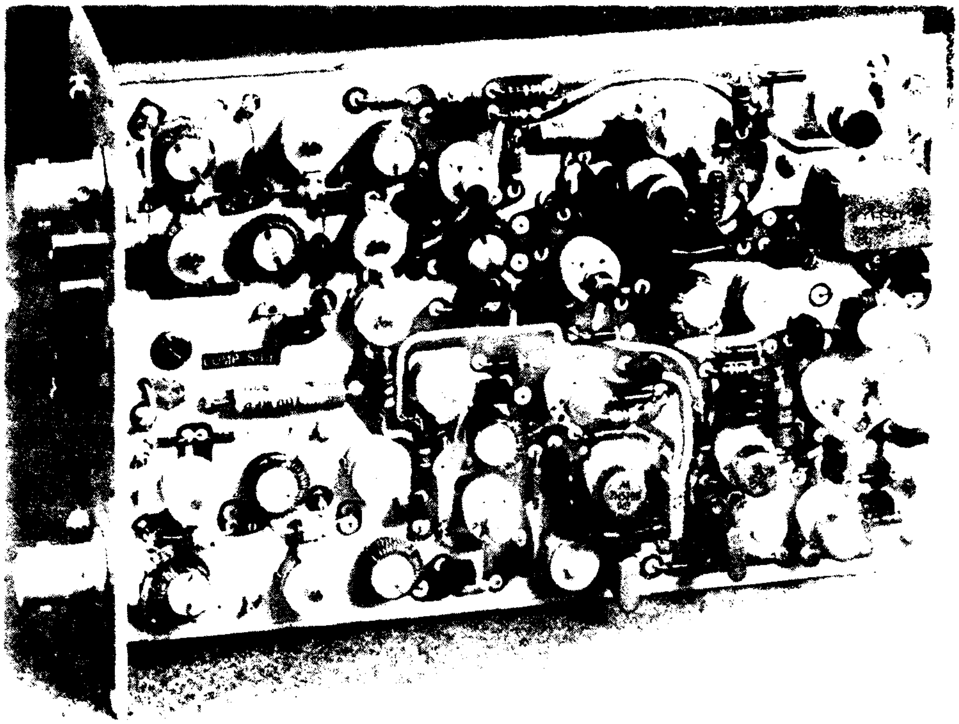

Figure 17. BCR-6A Board (Internal View)

6.6.1 FREQUENCY SELECTION

For this description, let us assume that the receiver is "locked" to one frequency input (P2). This means that 12 V are applied to pin A, and pin B is grounded. Both potentials are generated on the IF-audio board, and fed to the RF board. The potential (12 V) on pin A biases the RF amplifier on by applying a potential to gate 2 of Q1, activates the oscillator Q2 through R25, and finally deactivates the mixer through R5 by providing a cutoff bias to Q6. Because of the similarity of the dual RF sections of the receiver, only one circuit will be described. The signal flow of the RF input on P2 will be followed to the second intermediate frequency (IF) output (455 kHz) on pin D.

6.6.2 RF SIGNAL FLOW

The input signal on P2 is matched to approximately 50 ohms and then transformed by L1 to the impedance of a triple-tuned Butterworth band-pass filter consisting of L1, L2, L3, and its associated capacitors. (The design procedure

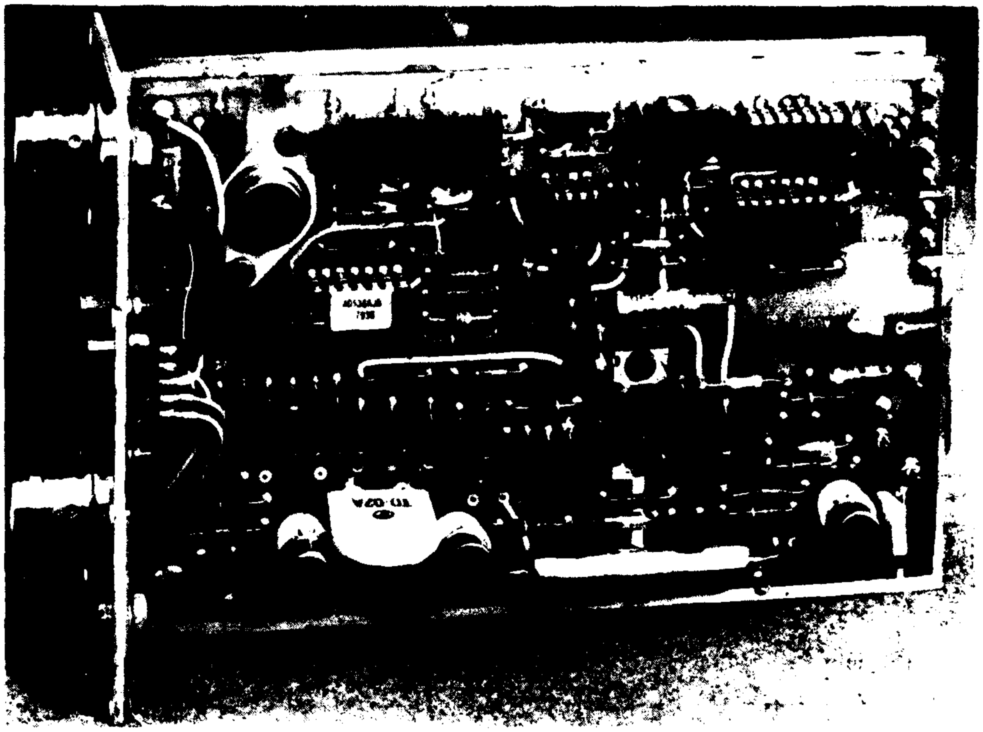

Figure 18. BCR-6A IF and Audio Board

for this filter is given in Ref. 7.) To prevent overloading of the receiver for signal levels of more than 1 Vrms, diodes CR1, CR2, and resistor R39 soft-limit the signal to the RF amplifier Q1. (Overload conditions can occur during balloon-launch preparations, when electrical noise and high RF signals are generated by ignition-spark radiation from launch vehicles, by radiation from walkie-talkie transmissions, and by radiation from high-power ground-control transmitters in close proximity to the receiver.)

At low signal levels, the diodes (CR1, CR2) do not affect the filter because their capacitance is very small and the equivalent resistance is high. This does not detune the filter, nor does it change the Q of the toroidal coils. At high signal levels, a large portion of the signal is bypassed to ground. This changes the percentage of modulation of the received signal and also lowers the Q of L1; however, L2 and L3 are still tuned to the center frequency of the received signal, thus maintaining band-pass filter action. During a balloon flight, received signals are much lower, and the limiting diodes have no effect on the band-pass filter.

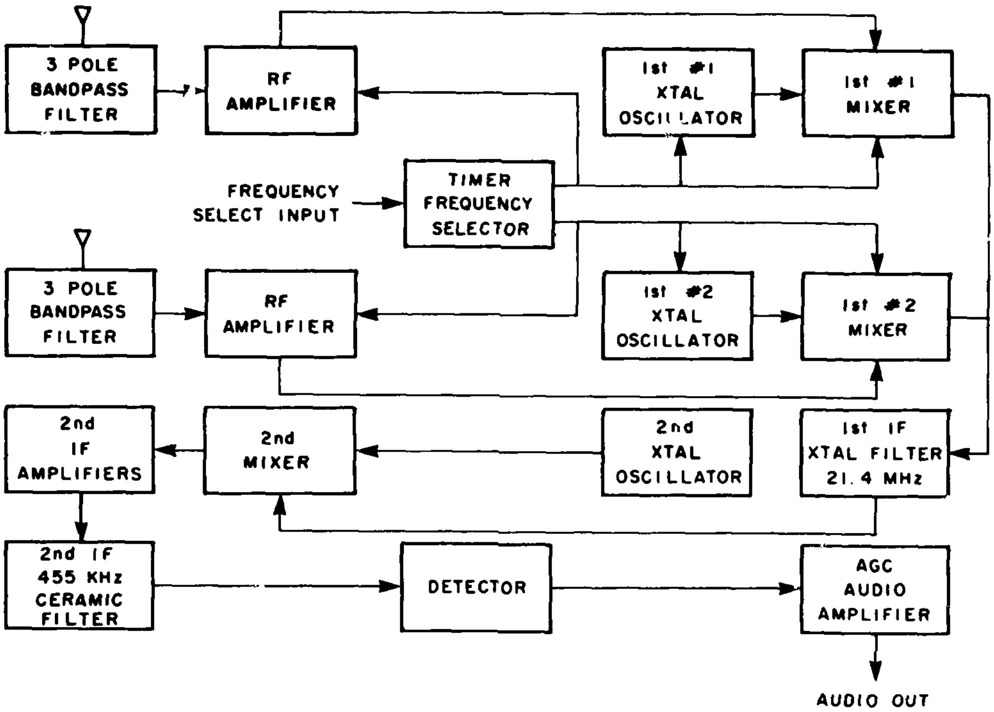

Figure 19. Block Diagram of BCR-6A Receiver

In this receiver design, an attempt was made to accomplish a high RF dynamic range, and at the same time provide a low dynamic range in the final output of the recovered modulation. This establishes a constant output to the command decoder. More detail will be included in the description of the audio amplifier. These two factors increase the security of any command system because the variation of RF signals, and a change in the percentage of modulation, still produce the same output to the command decoder. Any command system that uses narrow-band tone decoders should be designed in this manner, because the detection bandwidth of the decoders remains constant under all conditions of signal reception.

6.6.2.1 RF Amplifier

The filter output on L3 is coupled to gate 1 of Q1. This RF amplifier is a dual-gate, diode-protected, metal-oxide field-effect transistor (MOS FET depletion type) with numerous superior performance characteristics,[13] such as high signal handling capability, good linearity, low noise figure, low cross-modulation distortion, very low feedback capacity, and reverse AGC capability on gate 2, the same as the IF amplifiers. The low feedback capacity of the transistor ensures stability[14] throughout the HF range, and also provides good isolation between gate input signal and drain output voltage. The drain of Q1 feeds a tuned transformer (L4), which provides additional band-pass filtering and applies the RF signal to gate 1 of the mixer Q3. The oscillator signal from Q2 is applied to gate 2 of Q3. The combination of the RF and the oscillator signals provides a mixer frequency output of 21.4 MHz that is band-passed by L11, and then filtered again by a narrow-band crystal filter (FL-1).

6.6.2.2 Crystal Oscillators

All three crystal-controlled oscillators (Q2, Q6, Q10) are Colpitts type oscillators. The crystal frequency of the oscillators (Q2 or Q5) is the difference between the received signal frequency and 21.4 MHz. The exact frequency of each oscillator is adjusted by a variable capacitor (5-18 pf), connected in series with the crystal. This allows adjustment of each oscillator to the exact frequency required to produce 21.4 MHz with the received RF signal. The second oscillator signal from Q10 combines with the crystal filter (FL-1) output of 21.4 MHz, and provides the second IF signal of 455 kHz in the second mixer Q9. The output of the second mixer Q9 is tuned to 455 kHz, and fed to the IF-audio board where the modulation is detected and amplified to drive an associated command decoder.

6.6.3 IF-AUDIO AMPLIFIER BOARD

The second IF (455 kHz), the audio amplifier, the frequency selector-timer, and the regulator circuit are shown in the schematic diagram of Figure 21.

6.6.3.1 Regulator

External voltage (15-24 V) is applied to the regulator A8. Diode CR8 provides reverse polarity protection to the receiver. The fuse F1 (0.5 A) adds protection to the receiver for those rare occasions when a bypass capacitor fails, or when a

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13. Barr, L. S., RF Applications of the Dual-Gate MOS FET up to 500 MHz, RCA Application Note AN-4431, RCA Linear Integrated Circuits, Somerville, New Jersey.

14. Mitchell, M. M., and Lee, D. V. (1969) RF Applications of the N-Channel Dual-Gate MTOS Field Effect Transistor MEM 554, General Instrument Corp., Hicksville, New York.

short circuit to ground should develop in one of the solid-state devices. The regulator also provides fold-back current limiting that is somewhat higher than the current rating of the fuse, so that the fuse will blow before the regulator starts current-limiting. This is only true for a permanent short circuit developed in the receiver. During power turn-on when all bypass capacitors are being charged, instantaneous regulator current-limiting can exist without blowing the fuse because the capacitors become fully charged before the fuse can blow. The regulator A8 (12 V) assures constant performance of the receiver for a wide dynamic range (15 V to 40 V) of input voltages. During a balloon flight, the receiver is usually powered by a silver-zinc battery that can change from 1.86 V to 1.5 V per cell depending on the condition of the last charge cycle. Because the difference in capacity of a fully charged silver-zinc cell and a "despiked" cell is about 10 to 15 percent, the investment in a low-cost regulator more than pays for itself on the first balloon flight of the receiver. Battery preparation usually involves charging each cell to 2 V and then ("despiking") discharging it again to 1.5 V. The regulator eliminates this "despiking" procedure and effort.

6.6.3.2 Frequency Selector-Timer

A1A and A1B form an astable oscillator with an input of four times the desired frequency output of A2 (dual flip-flop). Q2 of A2 supplies power to the low-frequency section on the RF board and $\overline{Q2}$ selects the high-frequency section during the second half of the timing cycle of the flip-flop A2. Q2 and $\overline{Q2}$ continuously alternate from 12 V to ground, and select the proper RF section. The switching action of A2 is inhibited during testing when a logic 1 is applied to R2 (Reset 2) from pin L. This selects the $\overline{Q2}$ output and thus selects the high RF section; a logic 1 applied to S2 (Set 2) selects the low RF section.

During commanding, a ground potential is applied to pin 1 that is generated by the command decoder after a command channel becomes selected. This disables A1C and the flip-flop A2 remains "locked" to the proper RF section. Scanning action starts again after the removal of the command tone modulation from the received RF signal.

6.6.3.3 IF Amplifier Section

The IF output (455 kHz) from the RF circuit board is connected to pin C, which feeds the base of Q1. The collector of Q1 is matched to a very narrow band-pass ceramic filter (FL-1). The emitter is bypassed by a series resonant ceramic filter (FL-3), which enhances the gain at 455 kHz only, and provides additional selectivity for the IF signal. The output of filter FL-1 drives the gate of Q2, which is an enhancement mode V-MOS transistor. A small ferrite bead over the output lead of FL-1 is used to increase the stability of Q2. This transistor generates the

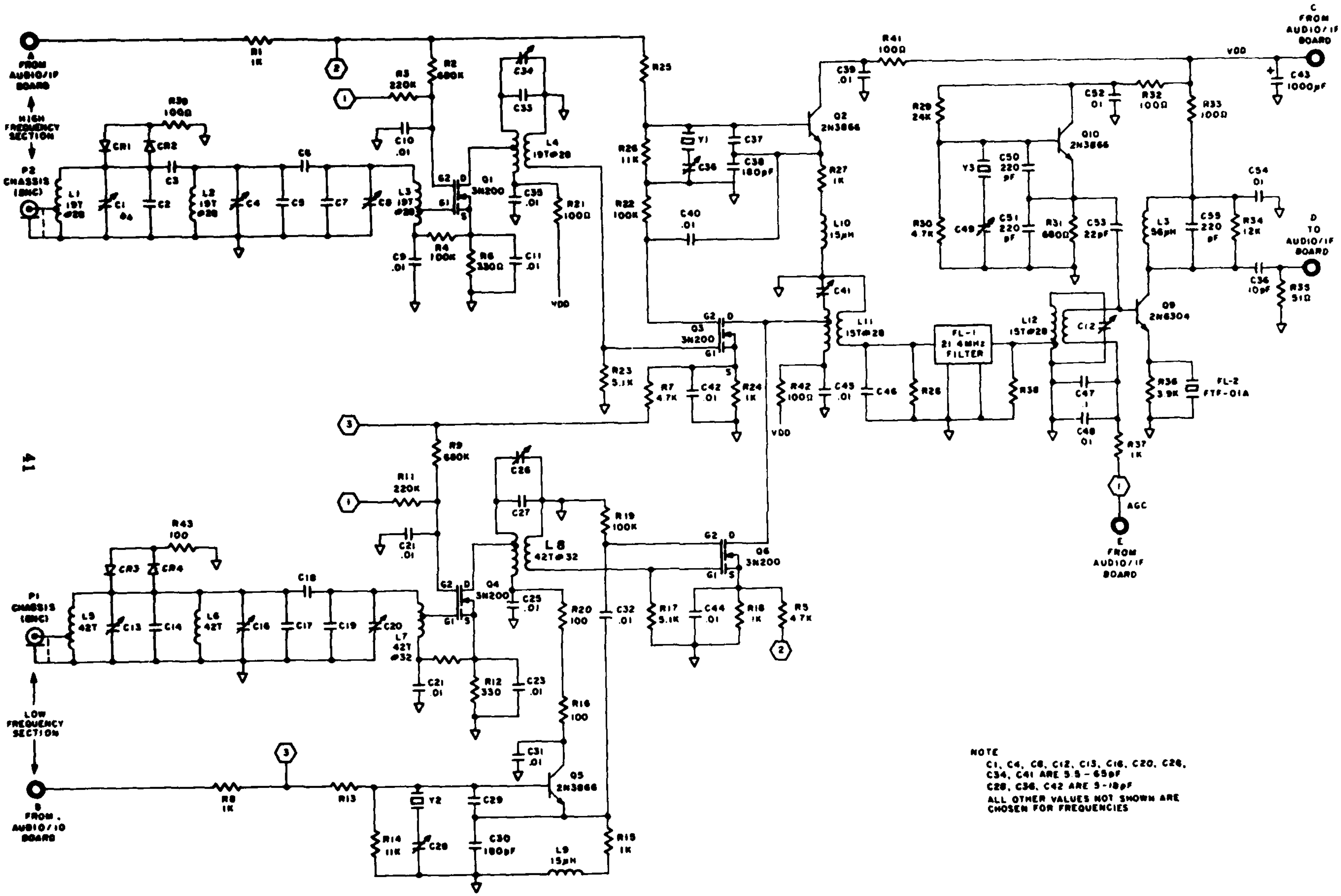

Figure 20. Schematic Diagram of BCR-6A RF Board

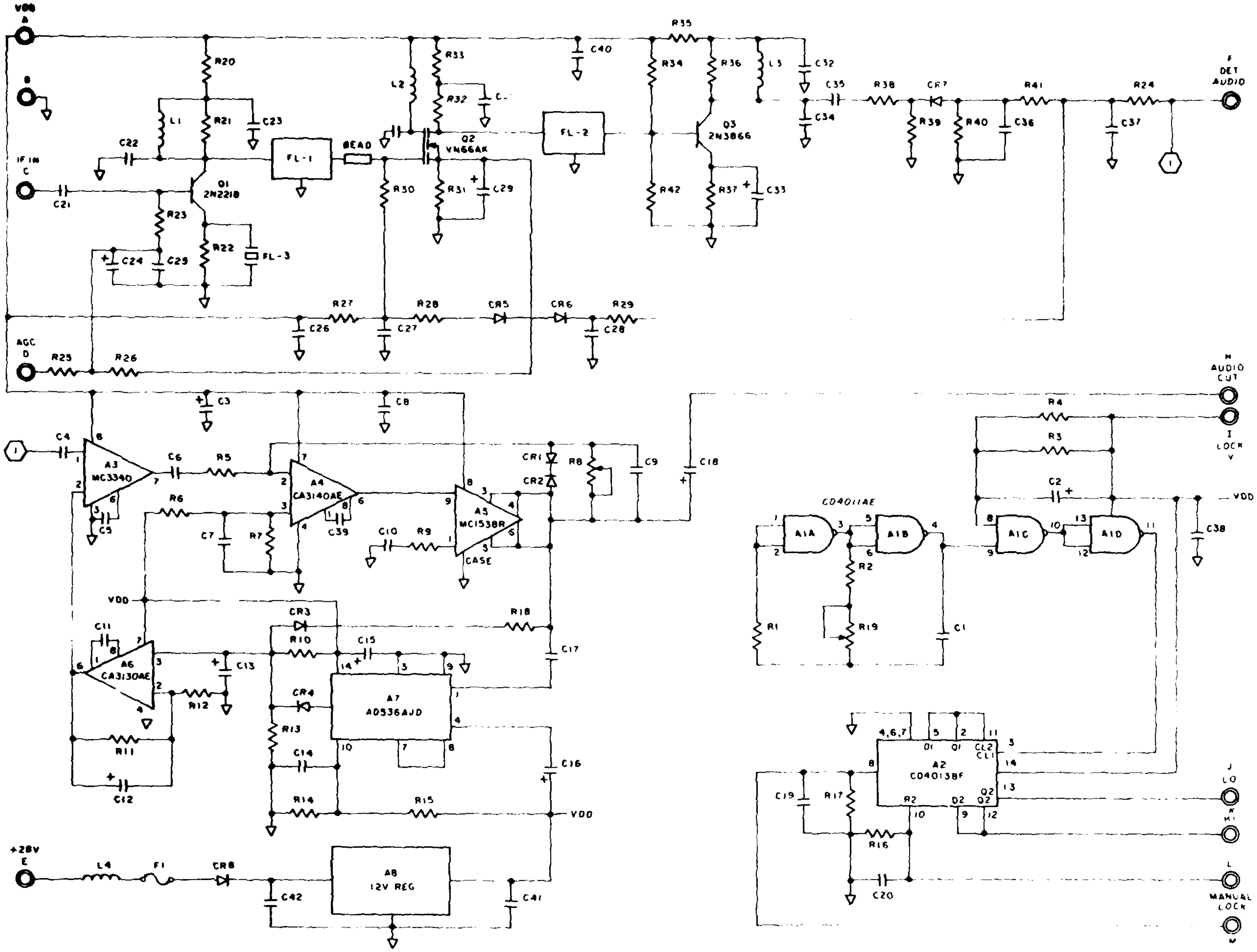

Figure 21. Schematic Diagram of BCR-6A IF-Audio Board

reverse AGC voltage for the entire receiver. The source voltage of Q2 changes with received signal strength. Detector diode CR7 establishes a negative bias across C36 when high RF signals are received. This negative voltage is fed back to the gate of Q2, which, in turn, lowers the voltage drop across R31. The net effect is a decrease in gain of all amplifiers biased from Q2.

Filter FL-2 couples the output of Q2 to the base of Q3. The amplitude modulated IF signal from the collector of Q3 is detected by CR7, low-passed by R41 and C37, and then applied to the audio preamplifier A3.

6.6.3.4 Audio AGC Amplifier

The detected audio signal is amplified by A3, the gain of which is controllable by a DC voltage applied to pin 2 of A3. The dynamic range of the output voltage from this electronic attenuator is typically about 80 dB. The combination of A4 and A5 amplifies the signal from A3 to the desired output voltage of 1 Vrms. This output voltage feeds a multi-channel command decoder, and simultaneously applies this signal to A7, which converts the rms voltage to a DC voltage level on pin 6 of A7.

As long as the input signal to A3, multiplied by the gain of A3 and A4, is less than 1 Vrms, the feedback loop of A7 and A6 will not activate. The voltage divider of R10 and R13 establishes a reference bias that is amplified by A6, and applied to pin 2 of A3. This sets the nominal gain of A3. Once the DC voltage on pin 6 of A7 is 0.7 V higher than the cathode voltage of CR4, the fixed bias across R13 increases, which also increases the output of A6 and, therefore, lowers the gain of A3. In this manner, changes in the input voltage of A3 will produce a constant output voltage from A5 once CR4 starts conducting. Diode CR4 provides a delayed AGC action so that linear gain is achieved until the output voltage reaches 1 Vrms.

Zener diodes CR1 and CR2 limit high noise spikes and prevent saturation of the audio amplifier for high input levels. Noise limiting, and the AGC action of the audio amplifier, are very important factors for any command decoder that is based on tone filters, because the bandwidth of each individual tone decoder remains constant, even if the percentage of modulation of the received signal is changed drastically, or when strong co-channel interference exists. Because the BCR-6A receiver operates in the HF spectrum, interfering signals from long distances and many sources can be detected and could cause audio saturation, thus decreasing the security of the command system. The AGC action of the audio amplifier in the BCR-6A receiver, multi-tone sequencing, and time delays used in the associated command decoder achieve the desired security and reliability in the balloon control system.

7. CONCLUSIONS

Two data transmitters and a command receiver were developed under In-House Work Unit 76591202. All design goals were achieved and verified by laboratory and actual balloon flight tests. Even though HF signals encounter many interference problems, this equipment can still provide economical solutions to long-duration, long-distance balloon flights where high data rates and instant command functions are not a prime requirement. This development augments standard IRIG compatible command control and data systems that are also available for those experimenters who need high data rates.

Many experiments can be served with the VHF/HF command and data system because balloon reaction time is generally very slow. Great flexibility can be achieved by utilizing a combination of an HF/VHF and an IRIG compatible control and data system for short- and long-duration balloon flights.

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