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THE VANGUARD SATELLITE COMMAND RECEIVER

NAVAL RESEARCH LAB WASHINGTON DC

09 SEP 1958

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ABSTRACT

The earth satellite command receiver has been developed at the request of Project Vanguard. This receiver turns on the satellite instrumentation upon command from a ground-based Minitrack station. The receiver is a VHF double-superheterodyne type utilizing a small portion of the 108-Mc Minitrack transmitter power as the first local oscillator. The basic design of the various components provides for economical use of satellite battery power and at the same time a reasonable degree of security against accidental interrogation from unauthorized sources.

PROBLEM STATUS

This is an interim report on one phase of the problem; work is continuing.

AUTHORIZATION

THE VANGUARD SATELLITE COMMAND RECEIVER

INTRODUCTION

The "Command Receiver" has been developed by the Electronics Division of the Naval Research Laboratory at the request of Project Vanguard, for use in certain Vanguard and other United States satellites. Upon interrogation by the proper signal from a ground station, this receiver turns on the more power-consuming satellite instrumentation and a telemetering transmitter for the transmission of scientific data back to the ground station. The use of this system greatly extends the life of the satellite batteries when the receiver power consumption is small in comparison to that of the telemetry system and the instrumentation. Also, it provides a method of receiving, at a ground station, scientific data stored in the satellite over portions of the orbit where no ground stations are located.

Receivers are being supplied to the following activities for use in Project Vanguard satellites: the Naval Research Laboratory, the United States Army Signal Research and Development Laboratory, and the University of Wisconsin. Also, receivers have been supplied to the Jet Propulsion Laboratory for use in the Army Explorer satellites carrying the cosmic-ray experiment which was transferred from the Vanguard program to the Explorer program. These units have given excellent operation throughout the satellite battery life. Minor modifications have been made when necessary to couple the units efficiently into the various satellite systems.

The receiver has been designed and constructed to conform to the standard Vanguard module (5-1/4 inches in diameter) and to be readily adaptable to various types of instrumentation. Through the use of printed circuit techniques and reliable subminiature components, the net receiver weight has been restricted to 5.2 ounces. The addition of 3 ounces of standard Vanguard plastic foam potting material increases the overall receiver module weight to 8.2 ounces and provides good reliability under conditions of shock and vibration.

Silicon transistors are used throughout the receiver in preference to germanium ones because of the superior temperature characteristics of silicon. Project Vanguard's specifications require proper operation over the temperature range from $0°$ to $60°$ C, with a minimum sensitivity of 90 db below one milliwatt. The variation in sensitivity with temperature for a typical receiver is shown in Fig. 1. The battery power required for operation of the receiver under standby or uninterrogated conditions is 16 milliwatts, and when the receiver is interrogated for short periods (0.6 seconds) the power consumed is approximately 200 milliwatts. Therefore, since the receiver is interrogated for considerably less than 1 percent of the time, the average power consumed is very nearly equal to the standby power of 16 milliwatts. Over the specification temperature range, the power consumption varies approximately ±20 percent about the nominal value. The basic power supply for the majority of the satellites consists of mercury primary cells which provide about 3.2 watt-hours of energy per ounce of battery weight (neglecting connecting hardware); thus, the operating life of the receiver is about 200 hours or 8.3 days per ounce of battery weight.

The receiver's pre-detection bandwidth is determined by the modulation frequency, the maximum expected doppler shift of the received signal, and the drift of the crystal-controlled oscillators with temperature. The Doppler shift of the received signal (Δf) may be calculated from the relationship
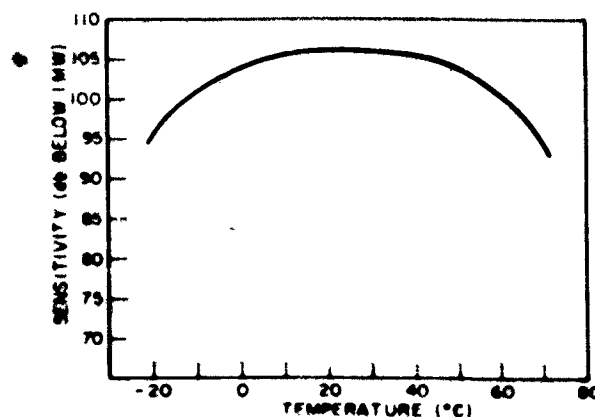
Fig. 1 – Typical curve of receiver
sensitivity versus temperature

$$\Delta f = f\left[\frac{\mp v}{c \pm v}\right] ,$$

where f is the transmitted frequency, c is the velocity of propagation of radio waves, and v is the relative velocity between transmitter and receiver. An assumed value of 150 Mc*
for f, and 5 miles per second for v,

$$\Delta f \approx \pm 4 \text{ kc.}$$

The expected drift of the local oscillators is approximately ±2 kc; therefore, a pre-detection bandwidth of 20 kc which allows 8 kc for modulation, was chosen as an adequate value.

GENERAL DESCRIPTION

The satellite command (Figs. 2 and 3) receiver is basically a double-superheterodyne crystal-controlled receiver. Approximately 1 milliwatt of power is coupled from the Minitrack 108-Mc oscillator for use as the first local oscillator in the receiver. The resulting first intermediate frequency is fed to the second converter, where the second intermediate frequency, 455 kc, is produced. After amplification, the modulation on the second intermediate frequency is recovered by the detector, which is a class B biased transistor. The audio signal from the i-f detector is filtered by a double-tuned circuit and then rectified to produce a dc signal. Two stages of current amplification are then used to actuate the output relay.

Circuits and coding techniques have been employed in the receiver to minimize the possibility of accidental turn-on by noise bursts or other types of unauthorized radiation. The proper modulation frequency must be used, and partial limiting of the second i-f signal before detection further requires that the signal be modulated at least 25 percent; also, an RC type integrator in the relay amplifiers requires that the signal be present in

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*The actual frequency is classified to prevent unauthorized interrogation which would, of course, waste battery power. However, 150 Mc is close enough for the Doppler computation.
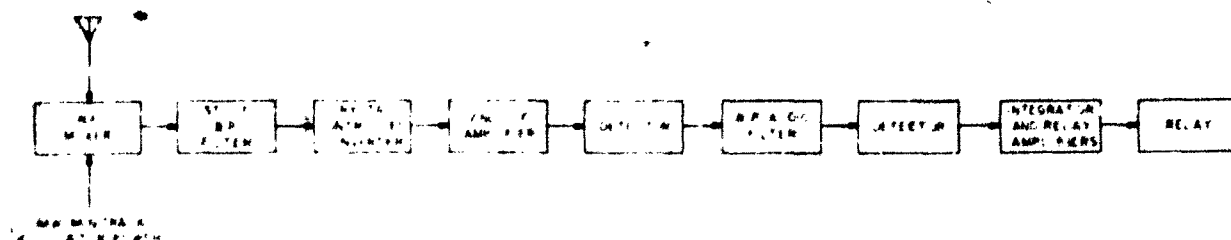
Fig. 2 - Receiver block diagram

the receiver passband for at least 0.1 second before relay closure will occur. More sophisticated methods of coding were not used because the added security was not considered worth the resulting penalty in weight and power consumption.

The general construction and layout of the receiver before potting are shown in Figs. 4, 5, and 6. The components were arranged to minimize the effects of electrical feedback and of rotational unbalance about the spin axis of the module.

CIRCUIT ANALYSIS

RF Mixer

The rf mixer is essentially a balanced mixer employing hybrid transformers on the input and output circuits. A balanced mixer was used in preference to the standard single-crystal type to prevent accidental relay closure due to modulation on the local oscillator signals. The Minitrack oscillators, from which the local oscillator signal is obtained, are in some cases modulated and could possibly cause "ring-around" difficulties. This modulation had the effect, in an unbalanced mixer, of varying the amplitude of the received signal in such a manner as to reduce the overall receiver sensitivity; the balanced mixer eliminated this problem, since the local oscillator modulation was not of sufficient magnitude to affect the conversion efficiency of the mixer crystals appreciably.

The hybrid transformer in this equipment is described in Appendix A. It is the electrical counterpart of several well-known devices such as the lumped-constant hybrid junction, the coaxial hybrid ring (the "rat race"), and the magic-T waveguide junction. The lumped-constant hybrid junction was rejected in favor of a hybrid transformer because the transformer was smaller, lighter, less sensitive to the adjustment of parameters, not sensitive to placement of nearby components, and more easily duplicated. A General Ceramics type 303 toroidal core made of Ferramic Q-2 was used in construction of the transformer which is 1/4 inch in diameter, 1/16 inch in height, and weighs only 1/4 gram. Transformers were used on both the input and output portions of the mixer with an impedance between the center tap of the output transformer and ground equal to the conjugate of the impedance seen looking into the transformer center tap. This provided a circuit that was not extremely sensitive to unbalance of crystal impedances and other network parameters.

The input networks were designed to match the mixer to the 50-ohm subminiature coaxial cables that supply the receiver with rf and local oscillator signals. Since a common antenna system is used for the Minitrack transmitter and the command receiver, a bridged-T null network tuned to 108 Mc was placed in the rf network. This provided a high degree of rejection of the Minitrack signal from the receiver and prevented any appreciable loading of the Minitrack signal by the receiver. Traps were placed in the rf network to obtain additional attenuation at the first intermediate frequency and the image of the input mixer.

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NOTE

1. RELAY IS ELGIN MODEL NMIC 500
2. ARGONNE I F TRANSFORMERS REWOUND FOR 20 KC BANDWIDTH
3. ALL TRANSISTORS ARE T 1 903'S UNLESS OTHERWISE MARKED
4. ALL VOLTAGE SOURCES DESIGNATED IN CELLS WITH MINUS TERMINALS GROUNDED
   1C = .13 VOLTS   2C = 2.7 VOLTS
   5C = .67 VOLT   8C = 10.7 VOLTS
5. ALL CAPACITOR VALUES ARE IN MICROFARADS UNLESS OTHERWISE MARKED
6. ALL RESISTOR VALUES ARE IN OHMS UNLESS OTHERWISE MARKED
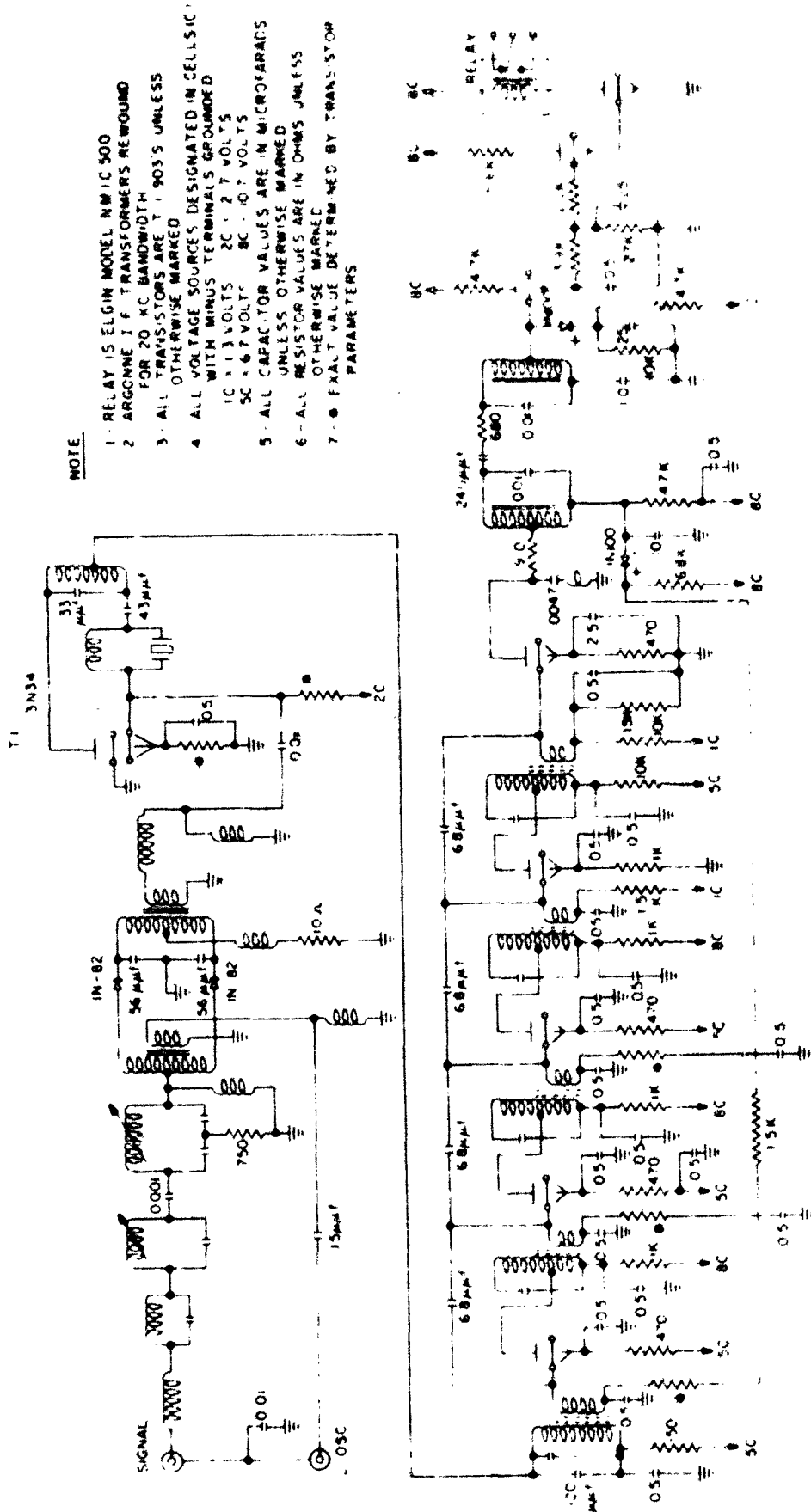7. * EXACT VALUE DETERMINED BY TRANSISTOR PARAMETERS
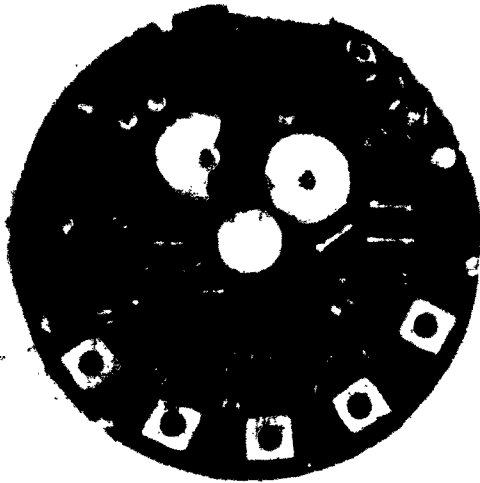
Fig. 3 - Receiver circuit diagram

Fig. 4 - Upper view of receiver
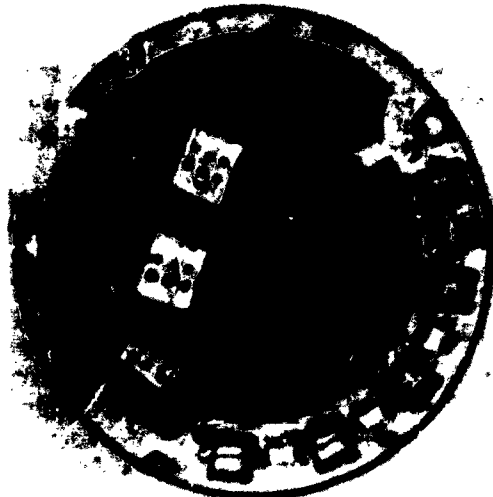before potting

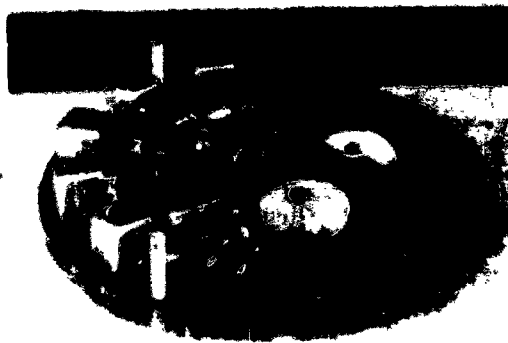Fig. 5 - Lower view of receiver
before potting

Fig. 6 - Oblique view of receiver
before potting

Certain satellites require operation of the receiver with power supplies that are common with other equipment and negative with respect to the satellite ground; therefore, the rf ground is separated from the dc ground or power supply return at the input terminals of the receiver through the use of capacitors. This also allows the receiver power supply to be located across any portion of the overall satellite battery pack in order to optimize relative current drains.

First I-F Converter

The first i-f converter is essentially a crystal-controlled oscillator that converts the first intermediate frequency to the second intermediate frequency of 455 kc, at which amplification and selectivity are more easily obtained. A type 3N34 silicon tetrode

transistor operated with conservative values of current was selected for this application.
The use of supply voltages of 6.7 and 2.7 volts, and currents of 0.5 and 0.2 milliamperes
for the collector and base circuits respectively provided reliable operation; however, the
variation in individual transistor characteristics under this condition of operation required
independent selection of emitter and base biasing resistors.

A special test network which simulated operating conditions was used to determine the
proper biasing resistors and to check each converter transistor for proper operation over
the required temperature range. This reduced the number of component changes and
hence the amount of soldering necessary in the printed-circuit module.

Frequency stability was attained by using a series resonant crystal in the feedback path
between the collector network and the transistor base. Since the first i-f signal also feeds
the base, the crystal holder capacitance was shunted by an inductance to form a broadly
resonant parallel circuit; this prevented loss of signal to the collector network and assured
oscillation at the series resonant frequency of the crystal.

The second i-f signal is extracted by means of an i-f transformer in series with the
collector supply. This transformer provides an impedance of approximately ten kilohms
at 455 kc and a very low impedance at the frequency of oscillation.

Second I-F Amplifiers and Detector

The second i-f amplifiers consist of four type 903 silicon transistors operated in a
grounded-emitter circuit and using single-tuned interstage coupling networks tuned to 455
kc. Large variations in beta cutoff frequency between individual transistors required
preselection by a special test network. With a collector voltage of 4 volts and a collector
current of 0.25 milliamperes, units were selected for an average gain of 20 db per stage
for each receiver. Transistors which did not yield the desired gain at i-f frequencies
were used in other portions of the receiver where high-frequency gain is no problem.

The first three stages are provided with AGC through the transistor base return leads.
Since the emitters of these stages are returned through decoupling resistors to the 5-cell
tap (6.7 volts) of the power supply and the AGC voltage can be driven negative with respect
to the 5-cell tap, highly effective AGC control is obtained. A germanium diode is used in
the AGC network to provide delayed AGC in weak-signal operation. The base biasing
resistors are adjusted individually in each receiver for collector currents of 0.25 milli-
amperes; this was found necessary because of the considerable variation in transistor
parameters and the desire to operate each stage in the most economical manner with
respect to power consumption.

The fourth i-f amplifier, which drives the detector, provides partial limiting of the
signal in addition to the desired gain. This prevents signals with less than 25 percent
modulation from closing the output relay and reduces the possibility that noise or other
extraneous signals might operate the receiver.

The overall receiver bandwidth is determined by the five synchronously tuned i-f
transformers. When the bandwidth is small compared to the i-f frequency, the relative
response of single-tuned, synchronously-tuned stages is

$$V = \left[1 + \left(\frac{2 \, \Delta f_0 \, Q_c}{f_0} \right)^2 \right]^{-\frac{n}{2}} \, .$$

where

f_0 = the center frequency,

Δf_0 = the deviation from f_0,

Q_c = the circuit Q, and

n = the number of tuned circuits.

The desired 6-db bandwidth ($V = 1/2$) for the receiver is 20 kilocycles; therefore, by substituting the values

$$V = 1/2,$$

$$2\Delta f_0 = 20 \text{ kc},$$

$$f_0 = 455 \text{ kc, and}$$

$$n = 5,$$

and solving for Q_c, the proper value of the circuit Q for each tuned network is found to be 12.9. By substituting this value of Q_c into the equation, the theoretical response curve of V versus Δf_0 may be plotted as in Fig. 7 which also shows measured response data from a typical receiver.
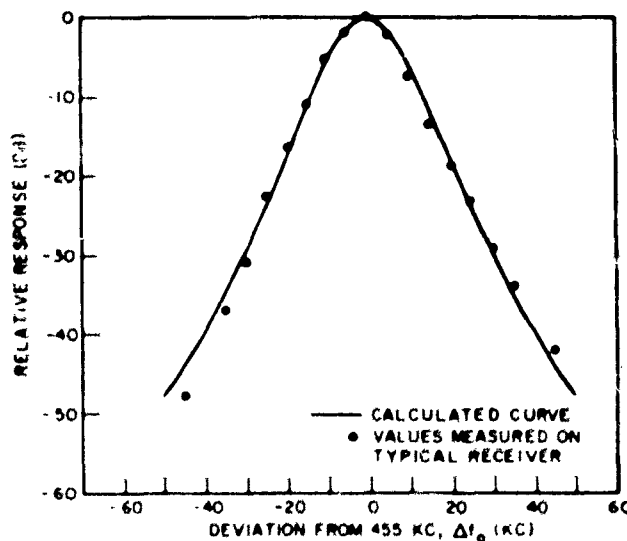

Fig. 7 - Command receiver second
i-f passband

Transistors are essentially power amplifying devices; therefore, interstage i-f transformers are designed to match input and output impedances to provide optimum power gain. Since practical transformers have finite values of Q, they represent additional circuit loading and thus a loss in gain. The network loss of a single tuned i-f transformer may be calculated from the expression:

$$\text{Transformer loss (db)} = 20 \log_{10} \left(\frac{Q_t - Q_c}{Q_t} \right),$$

where

Q_t = the transformer Q, and

Q_c = the circuit Q.

The i-f transformer coils used in this receiver have a Q of approximately 100; thus, since Q_c = 12.9, the above equation yields a circuit loss of 1.2 db per stage.

A collector type detector is used for detection of the second i-f signal. This method has the advantage of providing a considerable power gain while consuming very little battery power under standby conditions (when no interrogating signal is present). The detector is biased very near cutoff to give a collector current of 0.05 milliamperes. The addition of a parallel RC network in series with the emitter reduced the gain in the AGC loop; however, this helped reduce the tendency for the detector current to increase at high temperatures.

Audio Filter and Relay Amplifiers

The audio filter is a double-tuned circuit using capacitive coupling. Taps are located on the input and output inductances to provide proper impedance matching for the associated transistors. Tuning is accomplished by removing turns from each toroidal inductance until the desired resonance is obtained for each tank circuit. The value of the two resistors, which are closely associated with the filter, are such as to have negligible effect on its operation; however, they have a practical use in reducing the effects of feedback to the input portions of the receiver.

A germanium diode and a type 903 transistor form a peak-to-peak type detection circuit for rectifying the audio interrogation signal. The output network of this detector is an RC integrator which provides a 0.1-second delay before relay closure. Two dc current amplifiers following the integrating circuit provide sufficient current to actuate the output relay. The relay is a type NM1C500 manufactured by the Elgin National Watch Company. This device has single-pole double-throw contacts and weighs only 0.09 ounce.

The detector and relay amplifier stages are biased below cutoff by the voltage applied to the diode in the detector circuit. This voltage is adjusted for zero current drain in the presence of receiver noise, thus contributing to low power consumption.

ACKNOWLEDGMENTS

Appendix A
MINIATURE HYBRID TRANSFORMER DESIGN

The hybrid transformers are constructed on a ferrite toroidal core. By careful placement of the windings, the coefficient of coupling is made very nearly unity; therefore, impedances transform as the square of the turns ratio. The core material is selected for the highest possible permeability without excessive loss at the design frequency.

The basic schematic representation of the hybrid transformer is shown in Fig. A1. When identical loading impedances are connected to terminals 3 and 4, a signal in terminal 1 provides equal in-phase signals to the two impedances with zero signal to terminal 2, and a signal to terminal 2 provides equal push-pull signals to the two impedances with zero signal to terminal 1; conversely, in-phase signals at terminals 3 and 4 provide an output at terminal 1, and push-pull signals at terminals 3 and 4 provide an output at terminal 2.

The equivalent circuit as viewed by terminal 1 is shown in Fig. A2, where Z is the impedance loading terminals 3 and 4. The parameters L_1 and R_1 are determined for a particular transformer by shorting terminals 3 and 4 to ground and measuring the impedance between terminal 1 and ground. Transformer losses may be kept very small by designing $R_1 \ll$ real part of $Z/2$; also, L_1 should be kept small when large bandwidths are desirable. Further impedance matching and tuning were accomplished by using conventional circuit techniques.
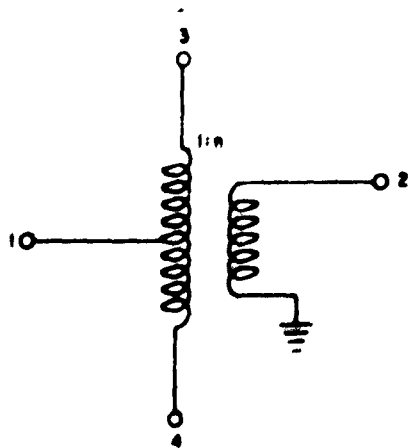

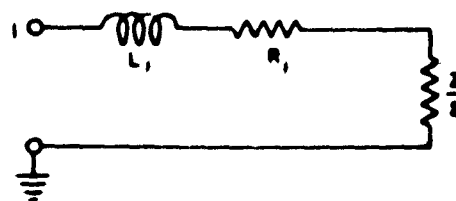Fig. A1 - Hybrid transformer schematic

Fig. A2 - Hybrid transformer terminal 1 equivalent circuit

The equivalent circuit as viewed by terminal 2 is shown in Fig. A3. The parameters L_2 and R_2 are determined for a particular transformer by shorting terminals 3 and 4, measuring the impedance between terminal 2 and ground, and subtracting the short-circuit impedance from the open-circuit impedance. Transformer loss may be minimized by designing

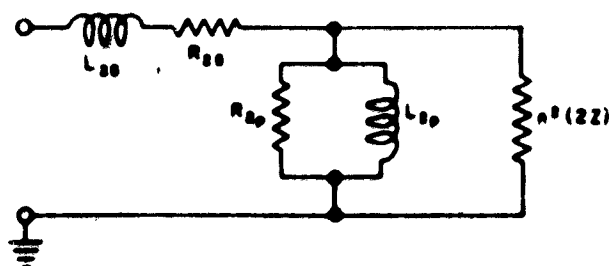$$R_2 \ll \text{ real part of } (n^2 2Z)$$

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Fig. A3 - Hybrid transformer
terminal 2 equivalent circuit

and

$$R_{2_p} \gg \frac{1}{\text{real part of } \left[\frac{1}{n^2 2Z}\right]} ,$$

where n is the turns ratio.

For large-bandwidth operation and ease of circuit design, it is desirable to have $L_{2_e} \ll L_{2_p}$. These inductances may be expressed as

$$L_{2_e} \approx (1 - k^2)L$$

and

$$L_{2_p} \approx k^2 L .$$

where L is the total inductance of the winding and k is the coefficient of coupling; therefore, it is desirable to have k as near unity as possible. In designing this transformer, it was helpful to keep in mind that the leakage inductance L_{2_e} is a function of the geometry of the windings and is affected very little by the core material.

* * *

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