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APOLLO SPACECRAFT SYSTEMS ANALYSIS PROGRAM
TECHNICAL REPORT
TASK E-9G

INVESTIGATION OF RECOMMENDED METHOD
FOR ELIMINATING TELEMETRY SPURS

NAS 9-8166

16 JANUARY 1970

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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1.0 INTRODUCTION

In accordance with NASA/TCSO letter EE8-69-5 dated September 10, 1969, TRW further investigated the method previously recommended by TRW in Reference 1 for eliminating the telemetry spurs which appear about the Apollo S-band downlink carrier center frequency.

The following results of this investigation are contained in this report:

- a) The bit-rate spurs caused by filtering the biphase modulated telemetry subcarrier prior to phase modulation were reduced 27 dB in the laboratory test setup.
- b) Half-bit-rate spurs, which appear when the telemetry signal is unsymmetrical in amplitude, were reduced 17 dB in the laboratory test setup.

2.0 THEORETICAL RESULTS

As shown in Reference 1, the biphase modulated telemetry subcarrier can be written as

$$f(t) = m(t) \sin(\omega_0 t) \quad (2-1)$$

where ω_0 is the subcarrier radian frequency and $m(t)$ is +1 or -1 depending on the state of the PCM-NRZ data. When $f(t)$ is passed through a symmetrical bandpass filter centered about ω_0 , the filter output* is

$$g(t) = x(t) \sin(\omega_0 t) \quad (2-2)$$

where $x(t)$ is the response of an equivalent low-pass filter on $m(t)$.

In the Apollo TM modulation process $g(t)$ phase modulates the S-band carrier of radian frequency ω_c . The result is

$$e(t) = A \sin \left[\omega_c t + \beta x(t) \sin(\omega_0 t) \right] \quad (2-3)$$

where β and A are constants. β is the modulation index when the maximum absolute value of $x(t)$ is 1. By the usual expansion by Bessel functions, $e(t)$ can be written as

$$e(t) = A \sum_{n=-\infty}^{\infty} J_n[\beta x(t)] \sin \left[\omega_c t + n\omega_0 t \right] \quad (2-4)$$

For $\omega_c \gg \omega_0$ the frequency components of $x(t)$, the components of $e(t)$ near ω_c result from the $n = 0$ term in Equation (2-4) and are

$$c(t) = A J_0 \left[\beta x(t) \right] \sin(\omega_c t) \quad (2-5)$$

where

$$J_0 \left[\beta x(t) \right] = 1 - \frac{\beta^2 x^2(t)}{4} + \frac{\beta^4 x^4(t)}{64} - \dots \quad (2-6)$$

is the zero order Bessel function of the first kind.

* The phase characteristic of the filter is assumed linear and equal to zero at ω_0 .

From the expression for $c(t)$, the spurs about the carrier are generated from the amplitude modulation of the carrier by $J_0 \left[\beta x(t) \right]$, where $x(t)$ is the amplitude variation of the filtered biphasic telemetry signal. If the lowest frequency component (Hz) of $x(t)$ is equal to one-half the bit rate (bps) then the spurs closest to the carrier are on either side of the carrier at a frequency of one bit rate away from the carrier frequency.

Since $J_0 \left[\beta x(t) \right]$ is an even function, its value does not change as long as the magnitude of $x(t)$ remains constant. Hence, if the telemetry signal in Equation (2-1) is not filtered and $m(t)$ is symmetrical with respect to amplitude (takes on only values of ± 1), then $x(t) = m(t) = \pm 1$ and no spurs are generated even if the telemetry signal is unsymmetrical with respect to time (unequal numbers of 1's and 0's).

The telemetry signal will be considered unsymmetrical with respect to amplitude when the magnitude of the positive value of $m(t)$ is different than the magnitude of the negative value of $m(t)$. For this case

$$x(t) = K + x'(t) \quad (2-7)$$

where K is the average value of $x(t)$.

When the argument of the Bessel function is less than 2.0, Equation (2-6) can be approximated by the first three terms on the right. From Equations (2-6) and (2-7)

$$J_0 \left[\beta x(t) \right] \approx 1 - \frac{\beta^2 [K + x'(t)]^2}{4} + \frac{\beta^4 [K + x'(t)]^4}{64}, \quad |\beta x(t)| \leq 2 \quad (2-8)$$

Expansion of the middle term on the right yields a contribution of $\frac{1}{2} \beta^2 K x'(t)$. It can be seen from Equation (2-5) that when $K \neq 0$ and $x'(t)$ has its lowest frequency component at one-half the bit rate, then the spurs closest to the carrier are on either side of the carrier at a frequency of one-half the bit rate away from the carrier frequency. $K \neq 0$ implies the telemetry is unsymmetrical with respect to amplitude and $K = 0$ implies the telemetry is symmetrical with respect to amplitude.

The spur reduction scheme proposed in Reference 1 was to first form

$$\begin{aligned} g^2(t) \sin(\omega_c t) &= x^2(t) \sin^2(\omega_o t) \sin(\omega_c t) \\ &= \frac{1}{2} x^2(t) [1 - \cos(2\omega_o t)] \sin(\omega_c t), \end{aligned} \quad (2-9)$$

then, after appropriately adjusting the amplitude, the above quantity was added to the phase modulated signal in Equation (2-3) to cancel the $x^2(t) \sin(\omega_c t)$ term in Equation (2-5). An alternate approach which accomplishes the same result is to form the product of $x^2(t)$ and $\sin(\omega_c t)$ directly where $x^2(t)$ is the square of the magnitude of the envelope of $g(t)$.

The proposed scheme will eliminate all spurs coming from the second term on the right in Equations (2-6) and (2-8). The technique cannot in general reduce spurs caused by higher order terms (which are small for small arguments) of $J_0[\beta x(t)]$. In some cases the higher order terms of $J_0[\beta x(t)]$ will have some components contained in $x^2(t)$ which can be reduced somewhat by the proposed scheme. This is especially true for the lowest frequency components of $x(t)$ which cause the spurs closest to the carrier frequency. An example of this is for a filtered square-wave telemetry signal.

Theoretical calculations were made for a filtered square-wave telemetry signal having unsymmetrical amplitude. (See also Section 3 of Reference 1.) The results are listed in Table 2-1 and show the reduction achieved in the half-bit-rate spurs when using the proposed scheme. Equation (2-8) was used with $K = 0.1$ and $x'(t)$ as shown in the table. After expansion of this equation the terms were grouped into carrier components, $\cos(\omega_c t \pm \frac{2\pi t}{T})$ terms (bit-rate spurs), and $\sin(\omega_c t \pm \frac{\pi t}{T})$ terms (half-bit-rate spurs). Spurs farther than $\frac{2\pi}{T}$ radians per second away from the carrier frequency were ignored. It was assumed that the carrier level was unaffected by the spur removal. This was the case in the experimental results to be discussed in the next section.

The results show that the bit-rate spurs can be completely eliminated even though the third term on the right of Equation (2-8) contributes to their amplitude. The half-bit-rate spurs are reduced approximately 22 to 25 dB for $\beta = 1.0$ and approximately 13 to 16 dB for $\beta = 1.5$.

Table 2-1. Spur-To-Carrier Ratios (in dB) for Filtered Square-Wave Telemetry with Unsymmetrical Amplitude (a)

Spur-To-Carrier Ratios (dB) for Spurs at Radian Frequencies Shown

Square Wave Components Passed by Bandpass Filter (b)	β	Before Spur Removal		After Spur Removal	
		$\omega_c \pm \frac{2\pi}{T} (c)$	$\omega_c \pm \frac{\pi}{T}$	$\omega_c \pm \frac{2\pi}{T}$	$\omega_c \pm \frac{\pi}{T}$
$x'(t) = \frac{4}{\pi} \sin\left(\frac{\pi t}{T}\right)$	1.0	-19.0	-29.6	$-\infty$	-54.5
	1.5	-11.0	-22.4	$-\infty$	-38.1
$x'(t) = \frac{4}{\pi} \left[\sin\left(\frac{\pi t}{T}\right) + \frac{1}{3} \sin\left(\frac{3\pi t}{T}\right) \right]$	1.0	-28.0	-29.2	$-\infty$	-51.6
	1.5	-19.0	-21.2	$-\infty$	-34.7

(a) Values in the Table are for $K = 0.1$ so the larger amplitude of $m(t)$ is 1.75 dB above the smaller amplitude.

(b) $2T$ is the period of the square wave and $\frac{1}{T}$ is the bit rate.

(c) The quantities listed are for either the spur at $\omega_c + \frac{2\pi}{T}$ or the one at $\omega_c - \frac{2\pi}{T}$.

3.0 EXPERIMENTAL RESULTS

The block diagram of the laboratory test setup for the spur reduction scheme is shown in Figure 3-1. (See also Figure 6-1 of Reference 1.) The circuit diagrams are shown in Figures 3-2 through 3-5. For test purposes, a carrier frequency of 950 kHz, a telemetry subcarrier frequency of 6 kHz, and a telemetry signal consisting of a 1 kHz square wave were chosen.

A means of adjusting the carrier phase was required in order to obtain the proper phase relationship between the spurs contained in the output signal from the phase modulator and the output signal from the balanced modulator. Potentiometer R2 in Figure 3-5 was used for this purpose. The importance of this phase relationship can be seen by considering, for example, reducing the amplitude of a sine wave by adding to it a second sine wave of equal amplitude and 180° phase difference. A phase error of 5° in the second sine wave results in only a 20 dB reduction of the first sine wave whereas a phase error of 2.5° results in a 27 dB reduction of the first sine wave.

The measured characteristics of the telemetry bandpass filter are shown in Table 3-1.

The amplitude of the output of the balanced modulator was adjusted with potentiometer R1 in Figure 3-4. R1 and R2 were simultaneously adjusted for maximum reduction of the spurs closest to the carrier.

For a telemetry signal with symmetrical amplitude, the bit-rate spurs at $(950 + 2)$ kHz and $(950 - 2)$ kHz were each reduced about 27 dB from an original amplitude of 12 dB below the carrier amplitude. The "before" and "after" photographs from an oscilloscope spectrum analyzer are shown in Figures 3-6 and 3-7. The spurious components remaining after reduction actually do not appear in Figure 3-7 since they are below the residual amplitudes of the stronger components near (950 ± 2) kHz. The components appearing at (950 ± 3) kHz result from the third harmonic of the telemetry square wave signal and are not spurs. Since the balanced modulator suppressed the carrier, removing the spurs did not affect the carrier level.

In addition to simultaneously reducing each bit-rate spur 27 dB, it was also possible to reduce one spur about 35 dB while simultaneously reducing the other spur 20 dB. This suggests some slight phase and amplitude unbalances between these two spurs in the circuit.

Measurements were also taken using square wave telemetry with unsymmetrical amplitude. The larger amplitude of the telemetry sub-carrier was 5.8 dB above the smaller amplitude (Equation 2-1). This extreme case was necessary in order to get spurs large enough to be measureable after reduction. The bit-rate spurs at $(950 + 2)$ kHz and $(950 - 2)$ kHz were reduced about 26 dB below their original amplitude of 16 dB below the carrier. The half-bit-rate spurs at $(950 + 1)$ kHz and $(950 - 1)$ kHz were reduced about 17 dB below their original amplitude of 16 dB below the carrier.

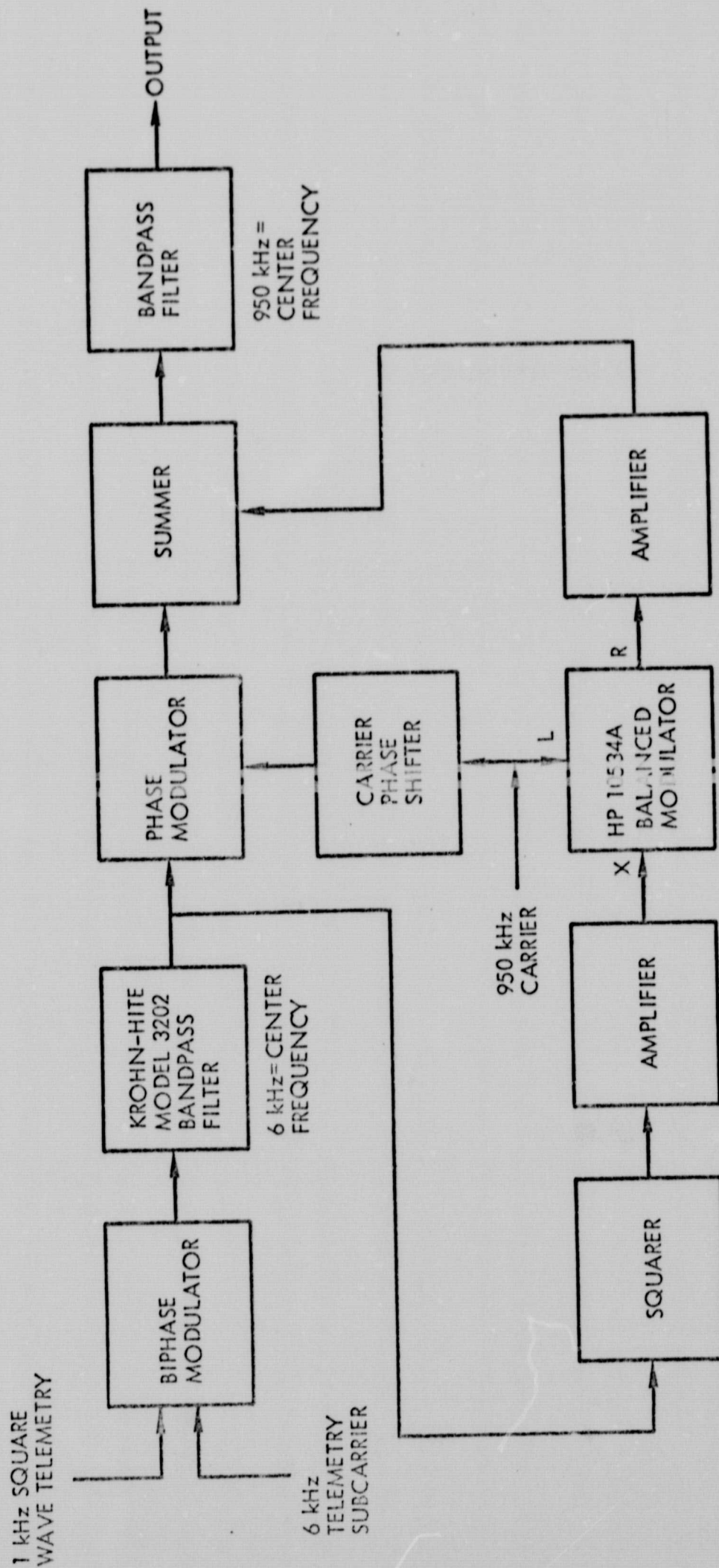


Figure 3-1. Block Diagram of the Laboratory Test Setup

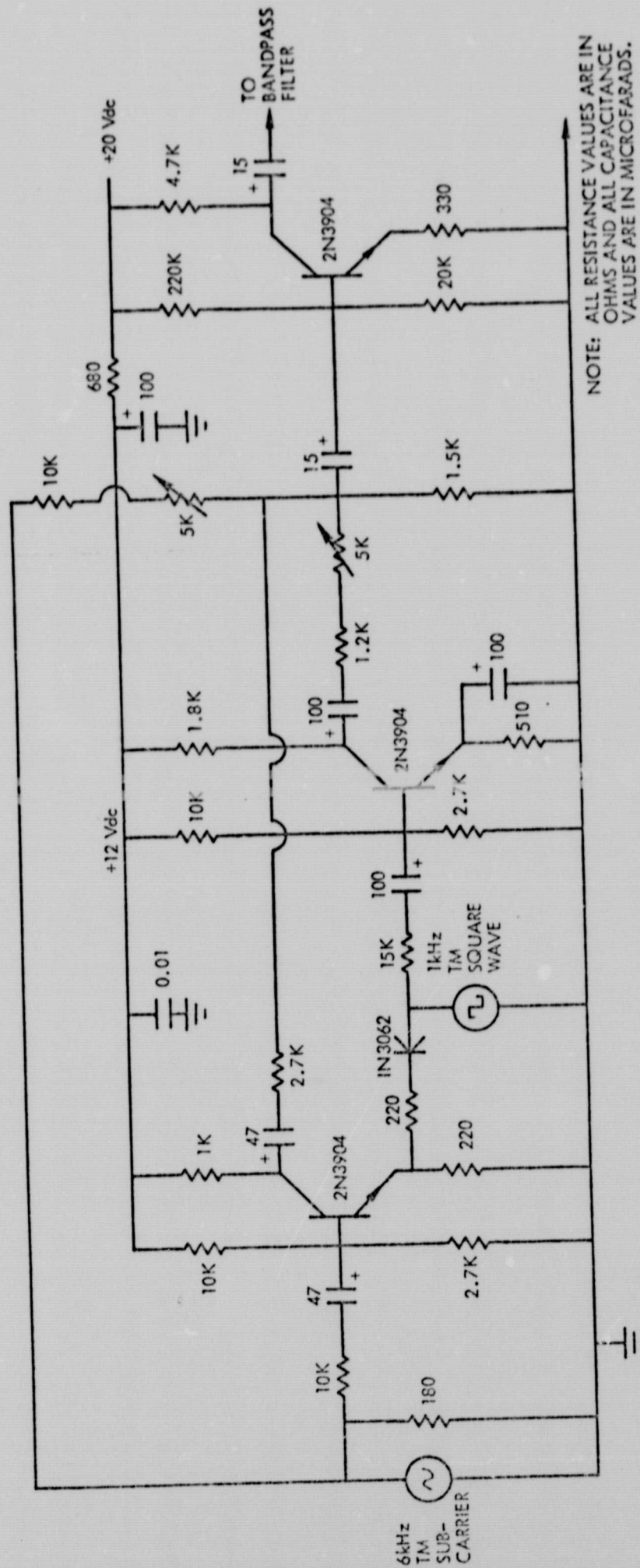
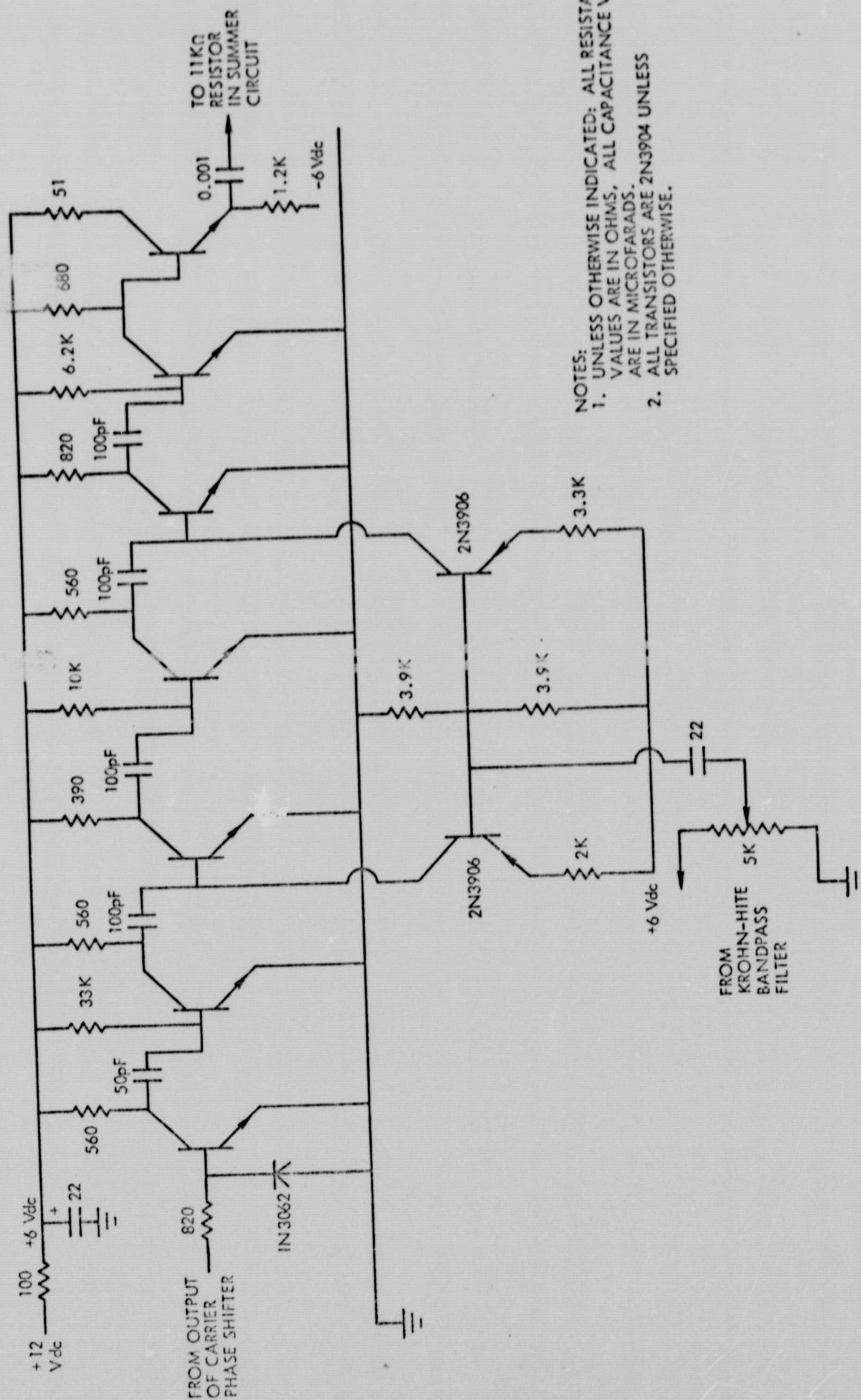


Figure 3-2. Biphase Modulator Circuit



NOTES:
1. UNLESS OTHERWISE INDICATED: ALL RESISTANCE
VALUES ARE IN OHMS, ALL CAPACITANCE VALUES
ARE IN MICROFARADS.
2. ALL TRANSISTORS ARE 2N3904 UNLESS
SPECIFIED OTHERWISE.

Figure 3.3. Phase Modulator Circuit

NOTES:
 1. ALL RESISTANCE VALUES ARE
 IN OHMS AND ALL CAPACITANCE
 VALUES ARE IN MICROFARADS.
 2. ALL DIODES ARE 1N3062.

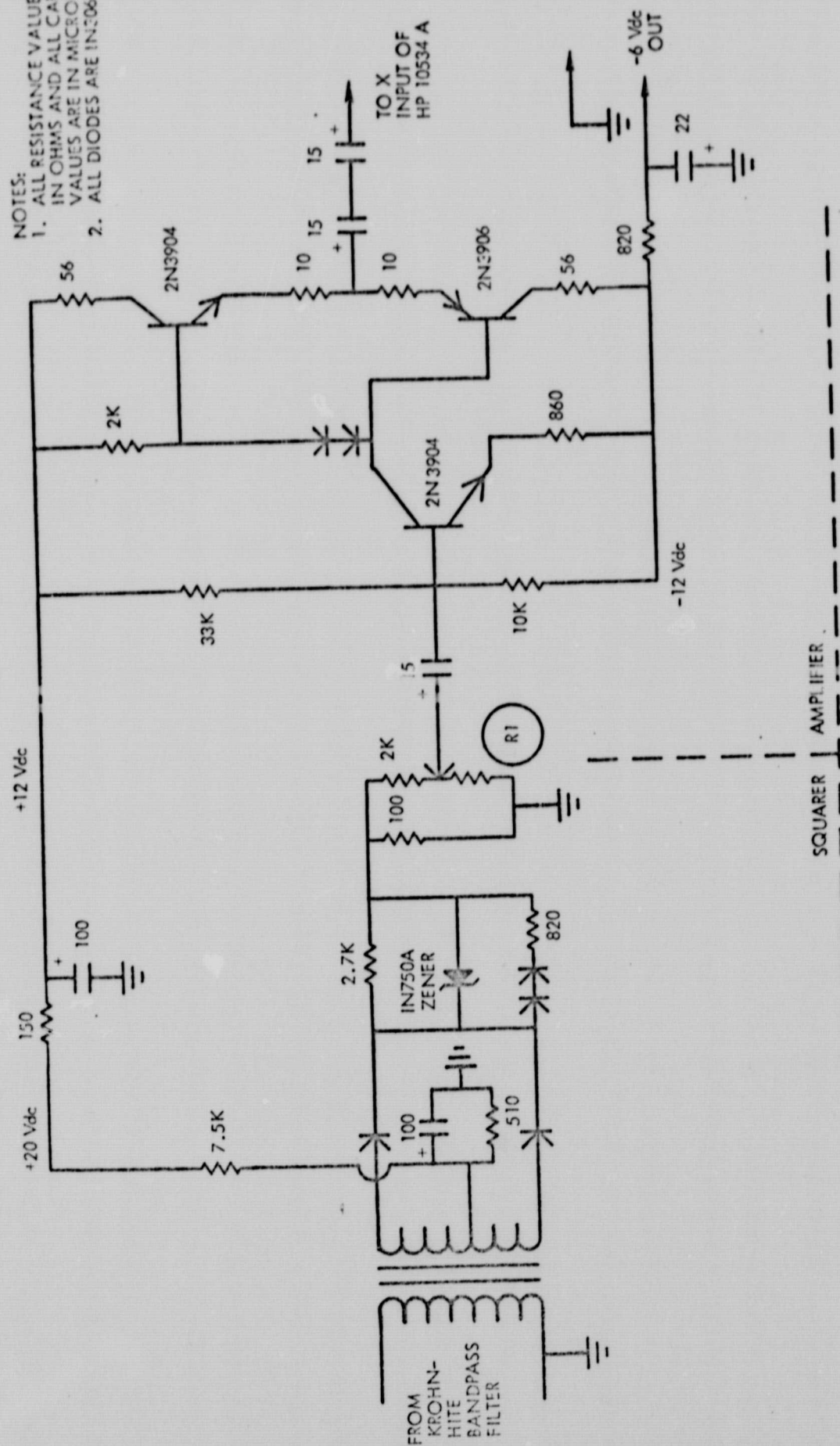


Figure 3-4. Squarer Circuit

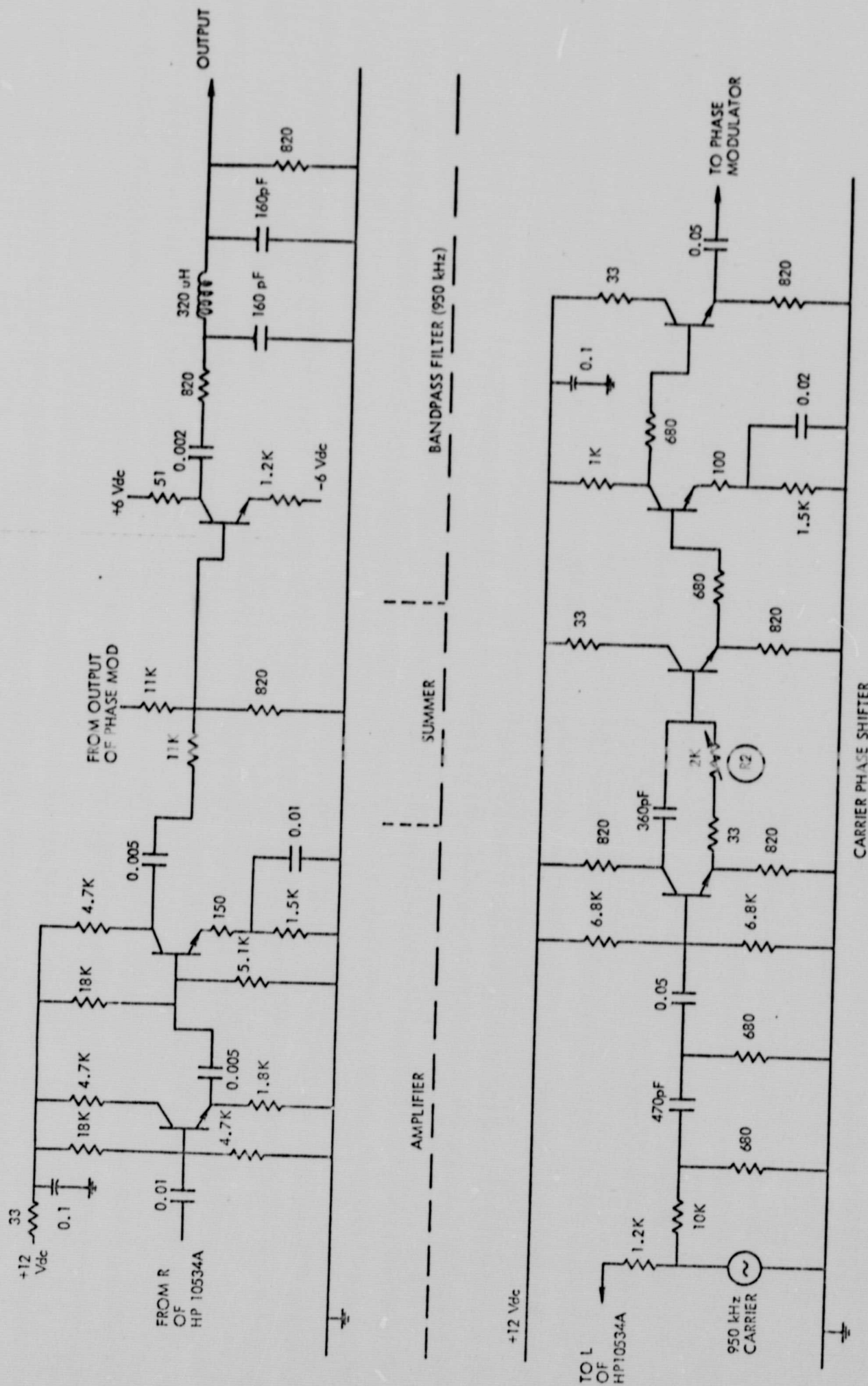


Figure 3-5. Carrier Phase Shifter, Summer, and Bandpass Filter Circuits

Table 3-1. Measured Characteristics of the Telemetry Bandpass Filter^(a)

Harmonic of Square Wave	Frequency ^(b) of Component (kHz)	Amplitude at Input to Filter (dB)	Amplitude at Output of Filter (dB)	Reduction of Components from Original Amplitude (dB)
Fifth	1	-14.8	-52.2	-37.4
Third	3	- 9.7	-25.4	-15.7
First	5	0.0	0.0	0.0
First	7	+0.1	-0.2	-0.3
Third	9	-9.3	-16.1	-6.8
Fifth	11	-13.6	-27.1	-13.5

(a) Krohn-Hite Model 3202.

(b) The input signal is a 6 kHz subcarrier which is biphase modulated by a 1 kHz square wave.

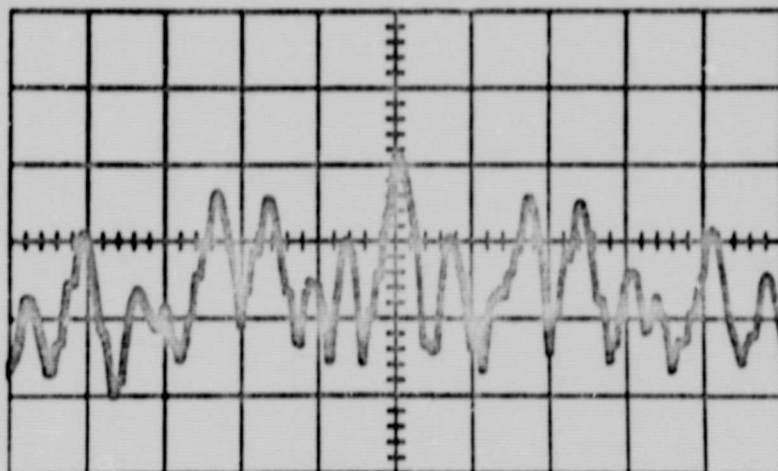


Figure 3-6. Amplitude Spectrum of the Sum Circuit Output Signal Before Spur Removal; Horizontal Scale: 3 kHz/cm; Vertical Scale: Approximately 10 dB/cm; Center Frequency 950 kHz

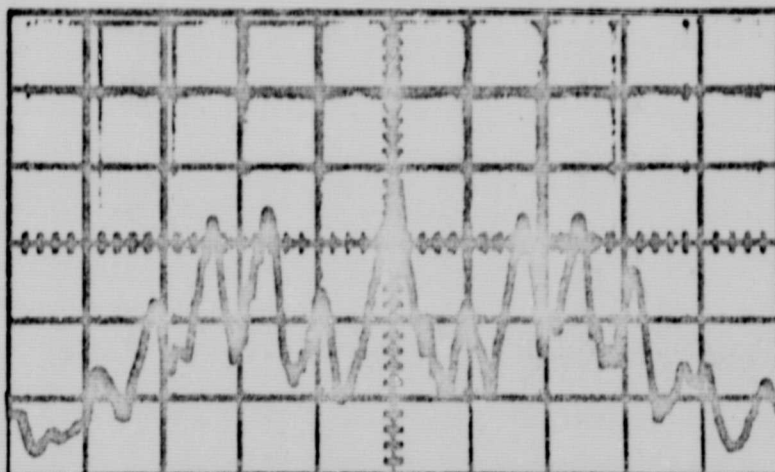


Figure 3-7. Amplitude Spectrum of the Sum Circuit Output Signal After Spur Removal; Horizontal Scale: 3 kHz/cm; Vertical Scale: Approximately 10 dB/cm; Center Frequency: 950 kHz

4.0 POSSIBLE EQUIPMENT FOR IMPLEMENTATION AT S-BAND

A carrier frequency of 950 kHz was used in the laboratory setup whereas the Apollo S-band downlink carrier frequency is 2,287.5 MHz. A brief survey was made of current equipment which could be used for implementation of the proposed spur reduction method at S-band. Some typical equipment is listed in Table 4-1.

Squaring the envelope of the filtered biphase - modulated telemetry subcarrier rather than squaring the signal itself allows operation of this circuit at lower frequencies. The current Apollo system uses a 1.024 MHz telemetry subcarrier which is biphase modulated with either a 51.2 kbps or a 1.6 kbps telemetry signal.

A variable attenuator could be used for the balanced modulator. Here gain varies with bias current and bias current could be made proportional to the modulating signal present at the output of the squarer. It may be necessary to use a feedback loop to have gain linearly proportional to the bias current over the operating region.

Table 4-1. Possible Equipment for Implementation of the Spur Reduction Scheme at S-band

Circuit Function	Equipment Manufacturer	Model Number	Comments
Squarer	Motorola Intronics, Inc.	MC 1595 M 510	Integrated Circuit Multiplier; dc to 750 kHz Multiplier; Size: 2 in x 3 in x 0.62 in; dc to 10 MHz
RF Amplifier	Hewlett-Packard	35802A	Solid State; Gain = 14 db at 1 GHz; 1.0 dB at 6 GHz
Carrier Phase Shifter	SAGE	6505	Coaxial type; Variable phase shift to 360° at 2 GHz; Size: 5 in x 5 in x 1 in
Balanced Modulator	Hyletronics	SS-144	PIN diode type variable attenuator; 2-4 GHz; Weight: 2 oz
Summer	Anzac	DCV-8850	Four way power divider summer; 2-2000 MHz; Volume: 23.4 cu in ; Weight: 11.5 oz
Divide Carrier into Two Sources	Aertech	M5202	Passive strip-line power divider for 2.2-2.3 GHz; Size: 3/4 in x 2 3/8 in x 2 1/4 in

5.0 SUMMARY

The proposed method of reducing spurs was tested in the laboratory using a square wave for the telemetry signal. The bit-rate spurs caused by filtering the biphase modulated telemetry subcarrier prior to phase modulation were reduced 27 dB. Half-bit-rate spurs, which appear when the telemetry signal is unsymmetrical in amplitude, were reduced 17 dB by the circuit. Hence, this method appears feasible for reducing these spurious components. In general, the proposed scheme will reduce any spurs about the carrier to the extent that $J_0 [\beta x(t)]$ can be approximated by terms through $x^2(t)$, i.e., a two term approximation.

It was also shown that spurs are not produced as a result of the telemetry signal being unsymmetrical with respect to time (unequal numbers of 1's and 0's).

REFERENCE

1. Ready, P. J., "Analysis of the Spurious Spectral Components Appearing About the S-Band Carrier," TRW 11176-H188-R0-00, 9 May 1969.