SCI

FINAL REPORT

EIGHT-CHANNEL TELEPHONE TELEMETRY SYSTEM

Contract No. NAS 9-12947

Submitted to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Manned Spacecraft Center

Houston, Texas

by

SCI SYSTEMS, INC.

8330 Broadway

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HOUSTON DIVISION

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Eight Channel EEG Telephone
Telemetry System

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1.0 INTRODUCTION

The analysis of EEG records is a talent and skill acquired over a long period of training and experience. For this reason, trained personnel capable of analyzing and diagnosing EEG records are in short supply. Such personnel are usually found only at the larger medical facilities. Hence, one normally expects a relatively long "turn around time" and inconvenience associated with either of the following:

1. Taking the record at a facility with EEG equipment but without personnel to interpret the record and then sending the record to another facility for analysis

   or

2. Requiring the patient to go to another facility for the service.

Hence, it is felt that technology derived from aerospace data handling experience could be applied to help alleviate this problem.

As such, this system, developed under Contract NAS 9-12947, is a portable, indirectly-coupled telephone system which will transmit to a central receiving site (by common voice-grade telephone line) eight channels of EEG data of sufficient fidelity for screening and/or limited diagnostic use. As such, the system:

1. Requires no electrical connection to the telephone at the transmitter or at the receiver (uses magnetic coupling)
2. Is compatible with common EEG recording practice for real-time recording
3. Will accept 8 input channels simultaneously with one telephone transmitter and one telephone receiver
4. Operates from standard power sources.

2.0 DESIGN CONSIDERATIONS

2.1 Frequency Versus Phase Modulation

As originally conceived, the transmitter utilized phase modulation. This allowed the center frequency of each channel to be locked to a common 100-KHz crystal by means of a phase locked loop; thereby providing excellent center frequency stability. After filtering, each channel was to be translated down to the audio range by mixing with the proper difference frequency.

In practical applications of phase modulation, the carrier can only be modulated at a level which produces a phase shift approaching 180°. For a 30-Hz modulating signal (the upper frequency limit of the system bandwidth) the maximum signal-to-noise (S/N) ratio was experimentally shown to be 23.5 db. For phase modulation, the frequency deviation is proportional to both the amplitude and the frequency of the modulating signal. Therefore, as the frequency of the modulating signal decreases, so does the deviation. The maximum S/N ratio for a 0.5-Hz signal (the lower limit of the system bandwidth) was observed to be only 16.5 db.

Consequently, for performance comparison, commercially-available equipment was used to implement a frequency modulation approach. When this was done, a S/N ratio of 30 db was observed. This S/N ratio was approximately constant for inputs from 30-Hz to d.c. Since a demonstrated increase in S/N ratio was realizable with frequency modulation, phase modulation was no longer considered for this project.

2.2 Transmitter Filtering

In the originally proposed system, the output of each modulator was passed through a bandpass filter prior to transmission. The concept was to reduce crosstalk to adjacent channels of data. Further analysis yielded the following.

The frequency spectrum of a sinusoidally modulated FM signal can be expressed as:

$$
\begin{aligned}
E(t) = A\ & J_0(B) \sin w_c t \\
& + J_1(B) [\sin (w_c + w_m) t - \sin (w_c - w_m) t] \\
& + J_2(B) [\sin (w_c + 2w_m) t + \sin (w_c - 2w_m) t] \\
& + J_3(B) [\sin (w_c + 3w_m) t - \sin (w_c - 3w_m) t] \\
& + \ldots\ldots
\end{aligned}
$$

where $Jx(B)$ = Bessel Functions

$B = \Delta f/f$ = modulation index

w_c = carrier frequency

w_m = modulation frequency

In the proposed system $B = 20/30 = .667$

$J_0(B) = 0.891$

$J_1(B) = 0.315$

$J_2(B) = 0.054$

$J_3(B) = 0.0093$

$J_4(B) = 0.00092$

$J_5(B) = 0.000073$

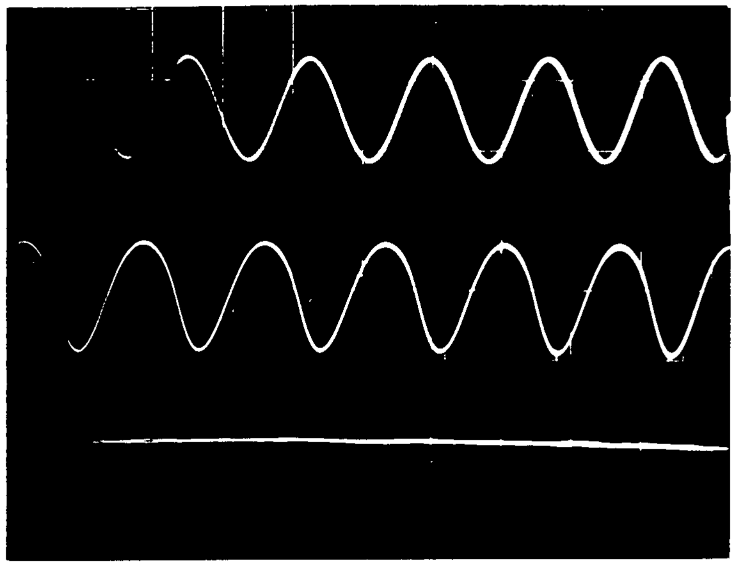
$J_6(B) = 0.0000048$

The specific purpose of the bandpass filters in the proposed transmitter was to filter out the higher order components of the series expansion that might lie in the bandpass of the other channels. Each of the eight channels required a crystal bandpass filter to reduce its modulated carrier to a constant bandwidth of 100-Hz. On close examination, the worst case condition would be for a 30-Hz modulating signal. The adjacent channel bandpass is centered 144-Hz from the channel of interest with a 100-Hz bandwidth. Thus, only the third harmonic (referred to w_m) and above need to be considered. Referring to the above listed table of coefficients one can see that the third harmonic component is only 0.03 of the first harmonic (Down 30.5 db). Furthermore, since the high-frequency components of the EEG are relatively small in magnitude, it was felt that these would be a minor problem. Hence, a decision was made not to provide bandpass filtering for the transmitter. This significantly reduced the complexity of the transmitter. Figure 2.2-1 is a photograph of representative data from demodulated adjacent channels. These data indicate that there is no significant crosstalk.

INPUT
(Channel 1)

OUTPUT
(Channel 1)

OUTPUT
(Channel 2)



5 v/cm

50 mv/cm

50 mv/cm

20 ms/cm

FIGURE 2.2-1

Input/Output/Crosstalk

2.3 Frequency Modulator

Examination of the foregoing analysis (Section 2.2) revealed further transmitter simplification could be achieved by modulating carriers operating at audio frequencies (1322 Hz, 1466 Hz, ..., 2330 Hz), thereby eliminating the need to translate radio freuqency carriers (100-KHz) to the audio range. As a direct result of this examination, a decision was made to use integrated circuit voltage controlled oscillators (VCO's).

Several crystal controlled FM circuits were investigated as possible alternatives to the VCO's. Deviating a crystal (an extremely high-Q circuit component) from its resonant frequency is not an easily linearized process. Of those circuits investigated, the most linear one (.65%) could only be deviated ± 415 Hz at 10 MHz before becoming too non-linear for use. This deviation corresponds to ± 4.1 Hz at 100 KHz, while the proposed transmitter requirement was ± 20 Hz at 100 KHz. This requirement was later changed to ± 40 Hz (see discussion in Section 2.4). Other circuits exhibited greater deviation but were grossly non-linear.

A basic building block, providing excellent linearity coupled with good center frequency stability, was found in the LM566 integrated circuit VCO. Figure 2.3-1 is a plot of the temperature stability of the VCO for Channel 1 and for Channel 8. For reference, the frequency of each channel's carrier is shown in Table 2.3-2.

Power supply rejection of the LM566 was shown to be adequate. Figure 2.3-3 is a plot of this power supply rejection. During the six weeks that the prototype system underwent engineering tests, the center frequency of all channels remained constant within 4-Hz.

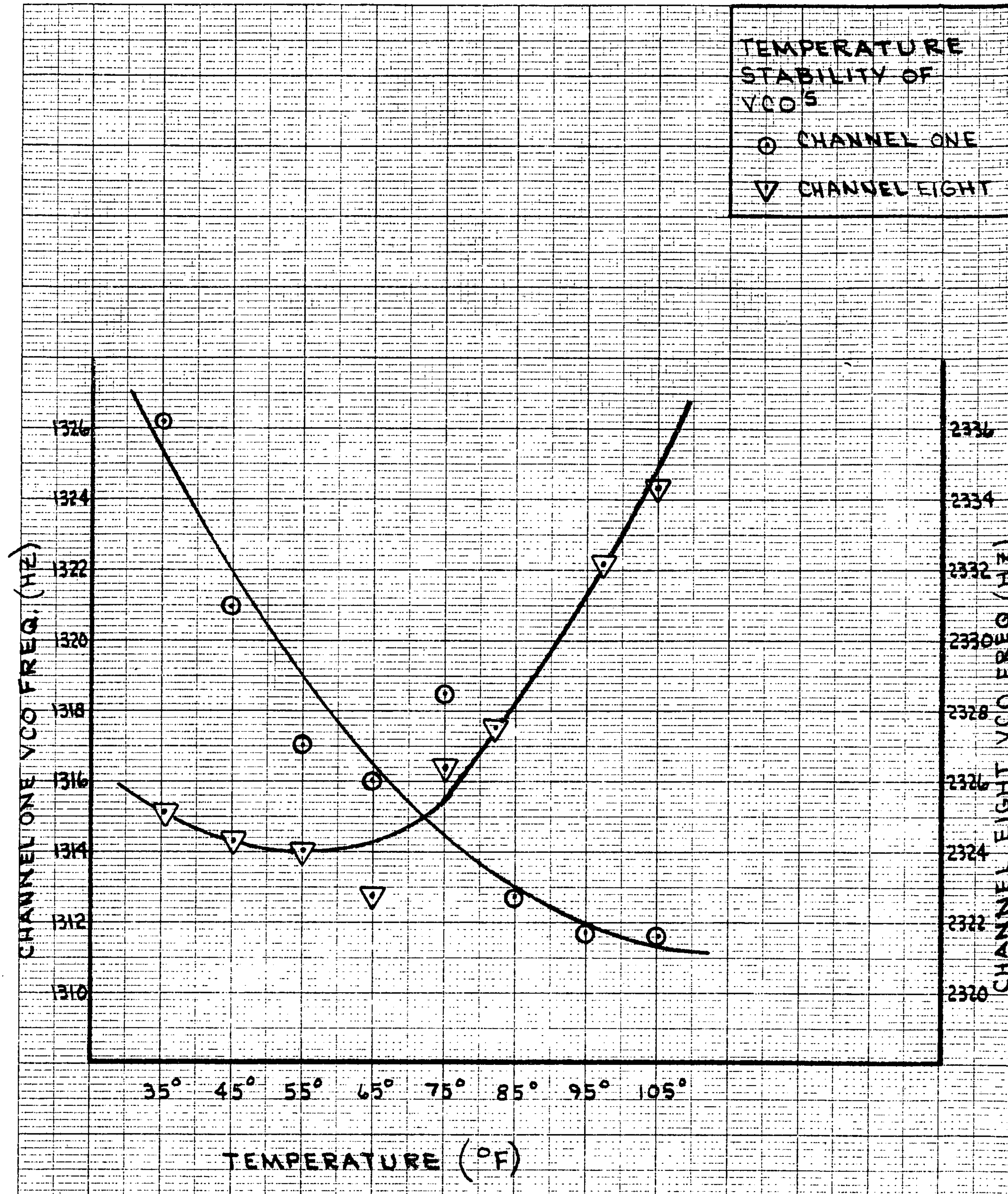

TEMPERATURE STABILITY OF VCO'S
CHANNEL ONE
CHANNEL EIGHT
CHANNEL ONE VCO FREQ. (HZ)
CHANNEL EIGHT VCO FREQ. (HZ)
1326
1324
1322
1320
1318
1316
1314
1312
1310
2336
2334
2332
2330
2328
2326
2324
2322
2320
35°
45°
55°
65°
75°
85°
95°
105°
TEMPERATURE (°F)
7

FIGURE 2.3-1

TABLE 2.3-2

Frequency of Carrier Signals for Each Channel

Channel 1	1322 Hz
Channel 2	1466 Hz
Channel 3	1610 Hz
Channel 4	1754 Hz
Channel 5	1898 Hz
Channel 6	2042 Hz
Channel 7	2186 Hz
Channel 8	2330 Hz

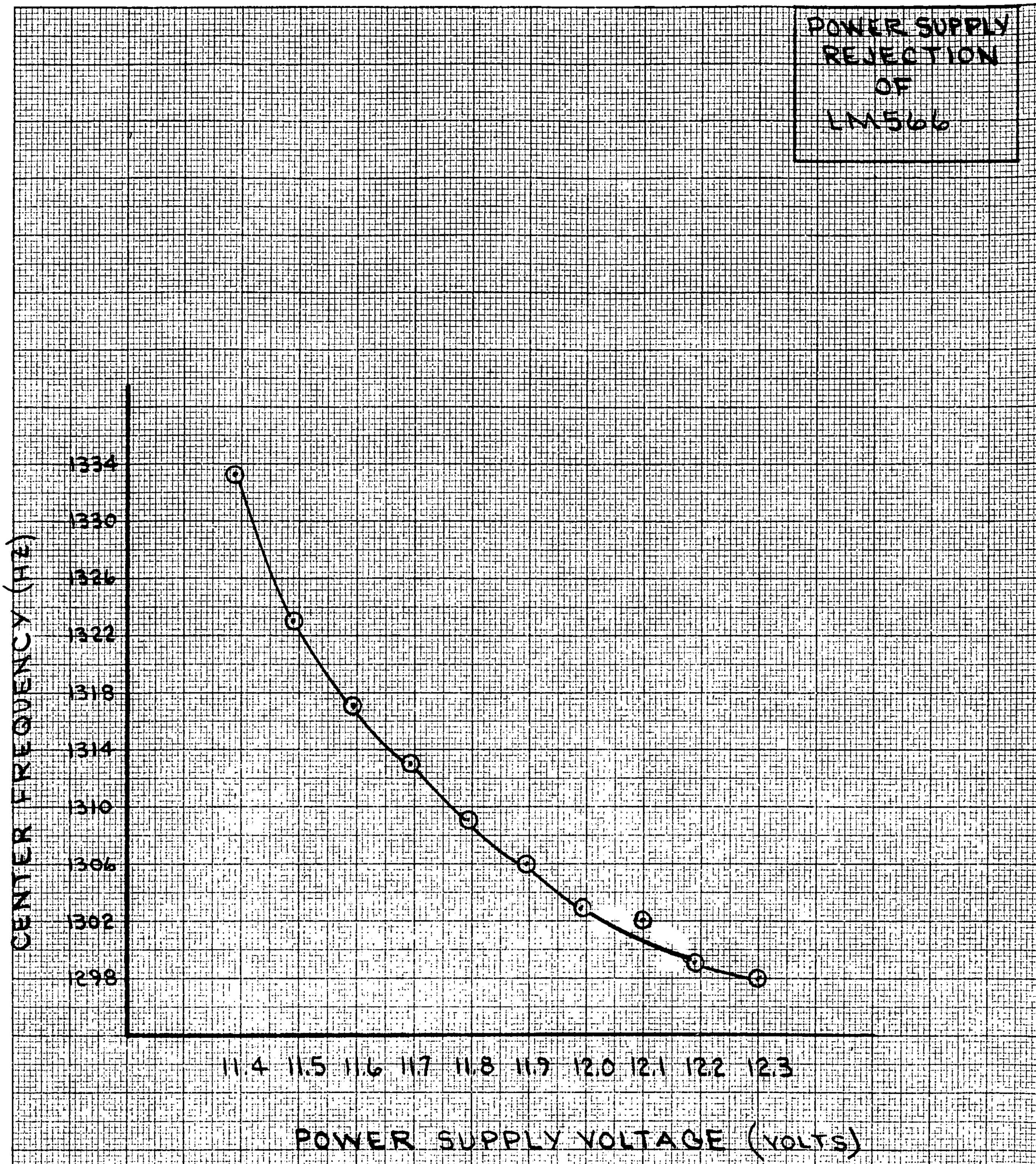

POWER SUPPLY
REJECTION
OF
LM566
CENTER FREQUENCY (HZ)
1334
1330
1326
1322
1318
1314
1310
1306
1302
1298
11.4
11.5
11.6
11.7
11.8
11.9
12.0
12.1
12.2
12.3
POWER SUPPLY VOLTAGE (VOLTS)

FIGURE 2.3-3

2.4 Maximum Frequency Deviation

Both the maximum frequency response and amplitude of each channel are determined by the bandwidth of the transmission channel. Each of the eight channels is separated from the other channels at the receiver by use of a bandpass filter.

The bandpass filters in the receiver have a 3 db bandwidth of 100-Hz, and the signal bandwidth of the system is .5 to 30-Hz. Thus, a maximum deviation of ± 20-Hz (corresponding to a modulation index of .66) is dictated by Carling's rule:

$$W = 2\,(Wm + f)$$

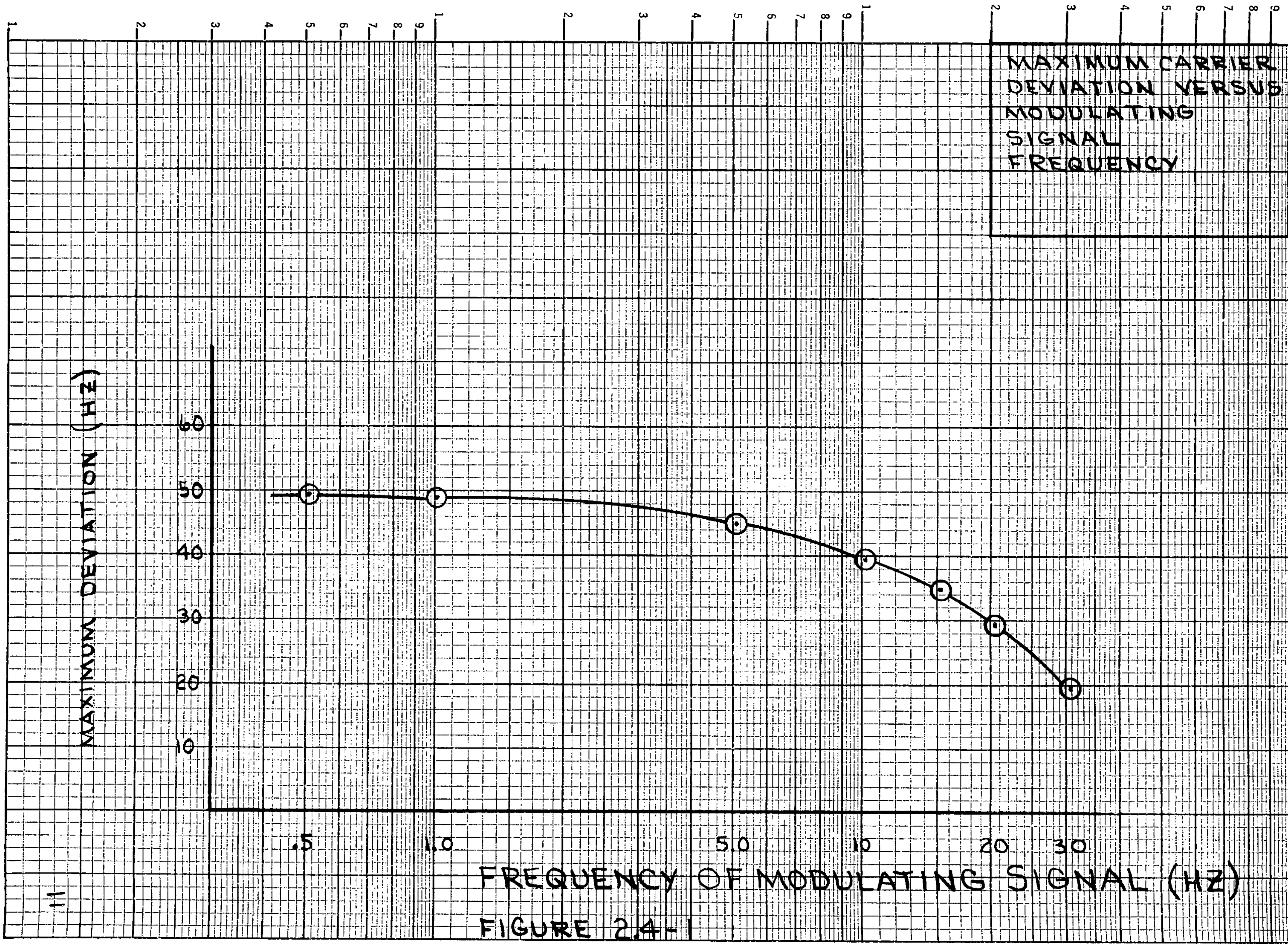
where W = transmission bandwidth (100-Hz)

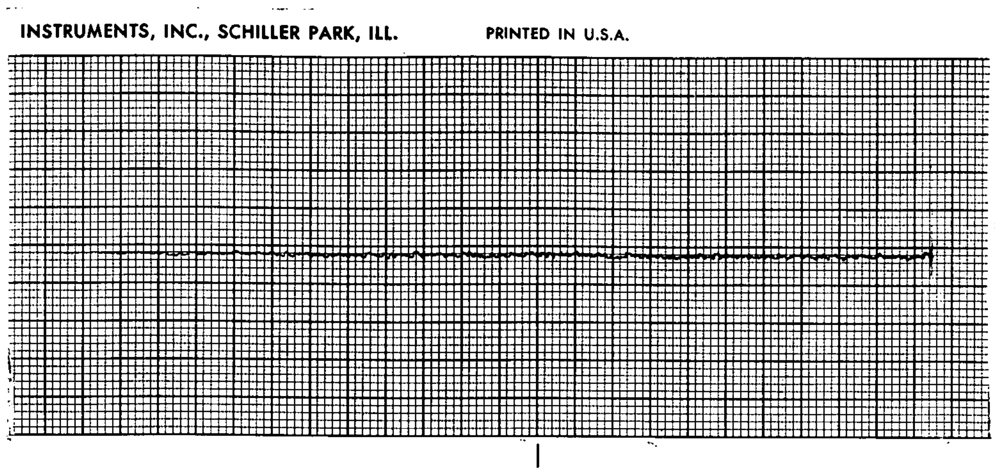
Wm = signal bandwidth (30-Hz)

f = frequency deviation

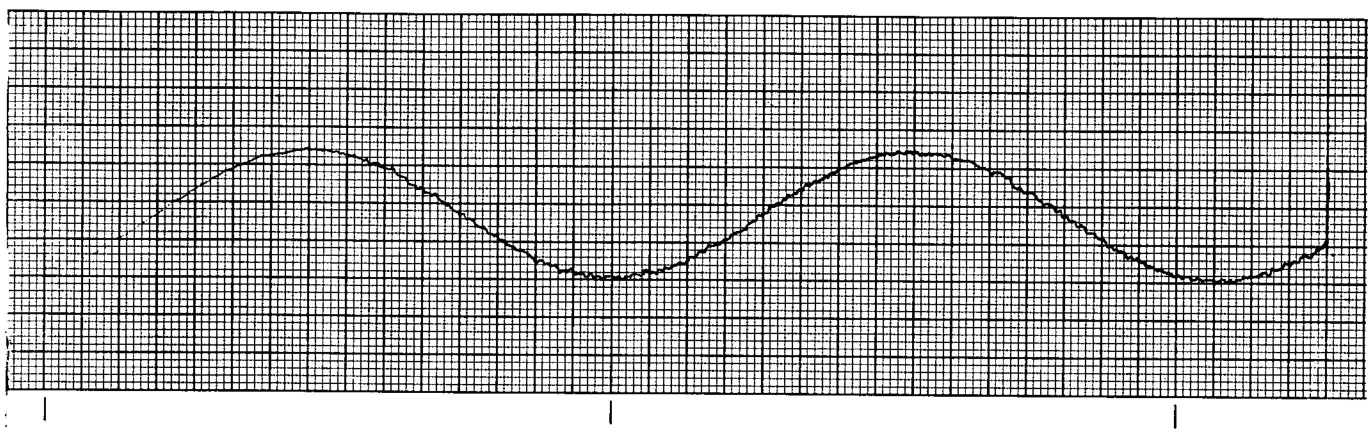
Test results showed the maximum S/N ratio to be 24 db while modulating the VCO with an index of .66. Increasing the S/N ratio would require increasing the maximum deviation, thereby decreasing the large signal bandwidth of the system. Figure 2.4-1 is a plot of the frequency dependence of the maximum allowable deviation before distortion of the signal occurs. This distortion, largely second harmonic in nature, would be decreased above 30-Hz by the 24 db/octave low-pass filter at the output.

As stated earlier, the high frequency components of the EEG signal are usually relatively small in magnitude. With this consideration in mind, the maximum deviation was increased to ± 40-Hz, resulting in a S/N ratio of 30 db. Figures 2.4-2 through 2.4-4 show that the small signal bandwidth remains as .5-Hz to 30-Hz. These data were obtained via a telephone link. A problem with 60-Hz interference is evident in Figure 2.4-3 but this was later found to be injected by the recorder (reference Figure 2.4-5).

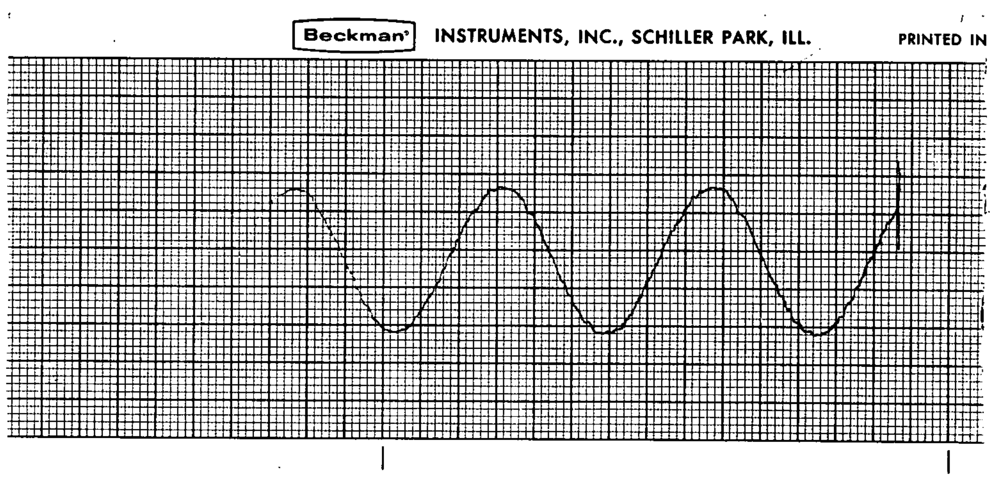

MAXIMUM CARRIER
DEVIATION VERSUS
MODULATING
SIGNAL
FREQUENCY
MAXIMUM DEVIATION (HZ)
60
50
40
30
20
10
.5
1.0
5.0
10
20
30
FREQUENCY OF MODULATING SIGNAL (HZ)
FIGURE 2.4-1



Baseline Noise 25 mm/sec; 1 v/cm

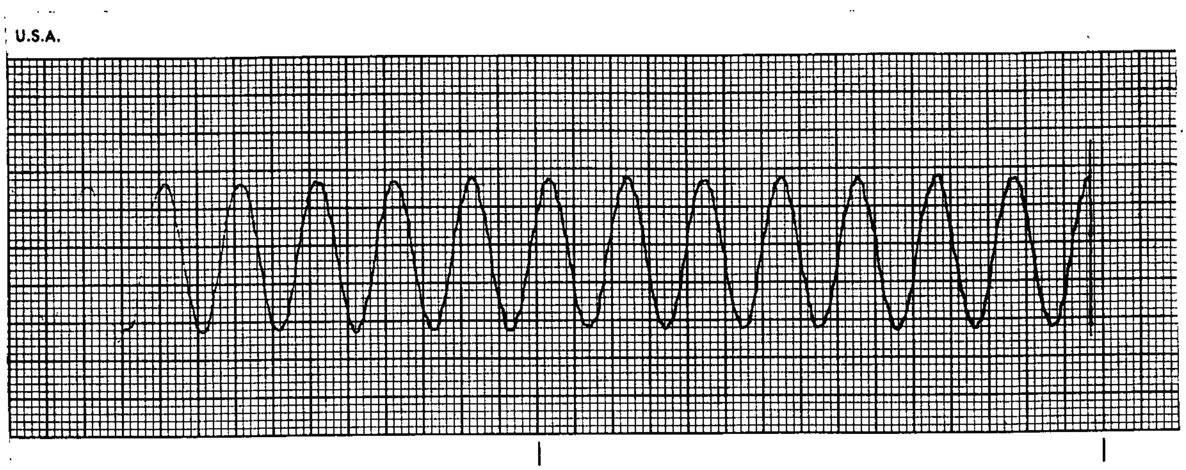


.4 Hz signal 25 mm/sec; 1 v/cm

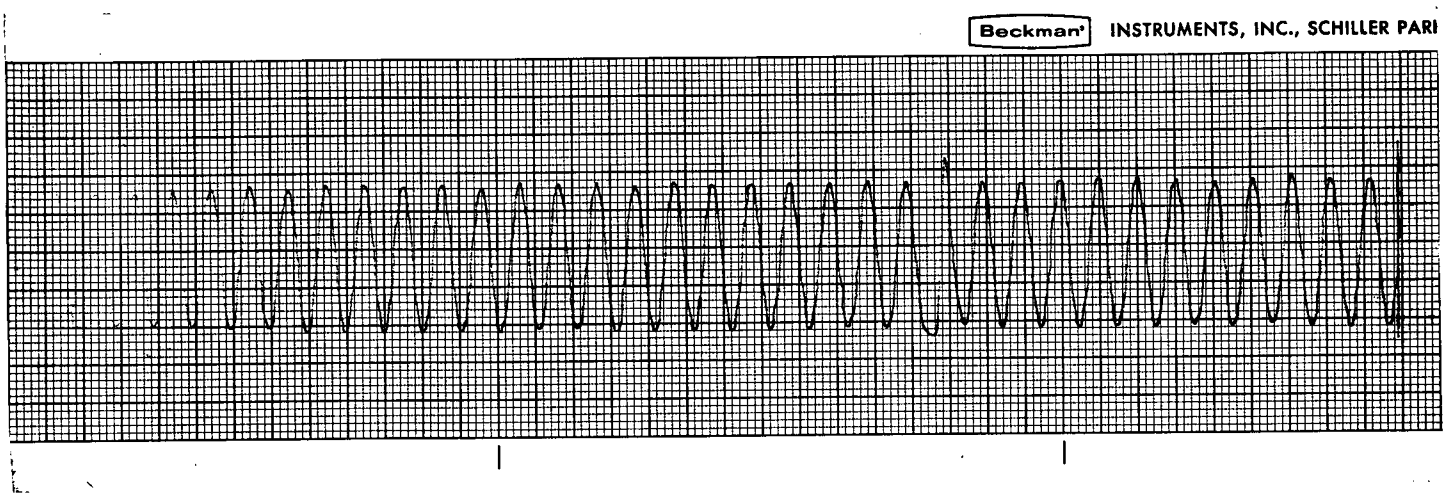


1 Hz signal 25 mm/sec; 1 v/cm

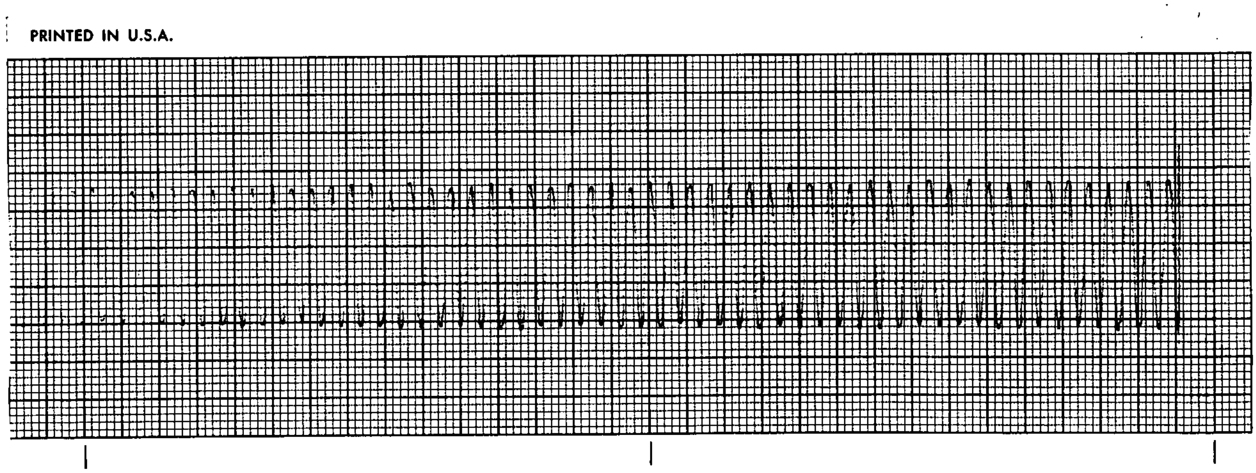
FIGURE 2.4-2



5 Hz Signal 50 mm/sec; 1 v/cm

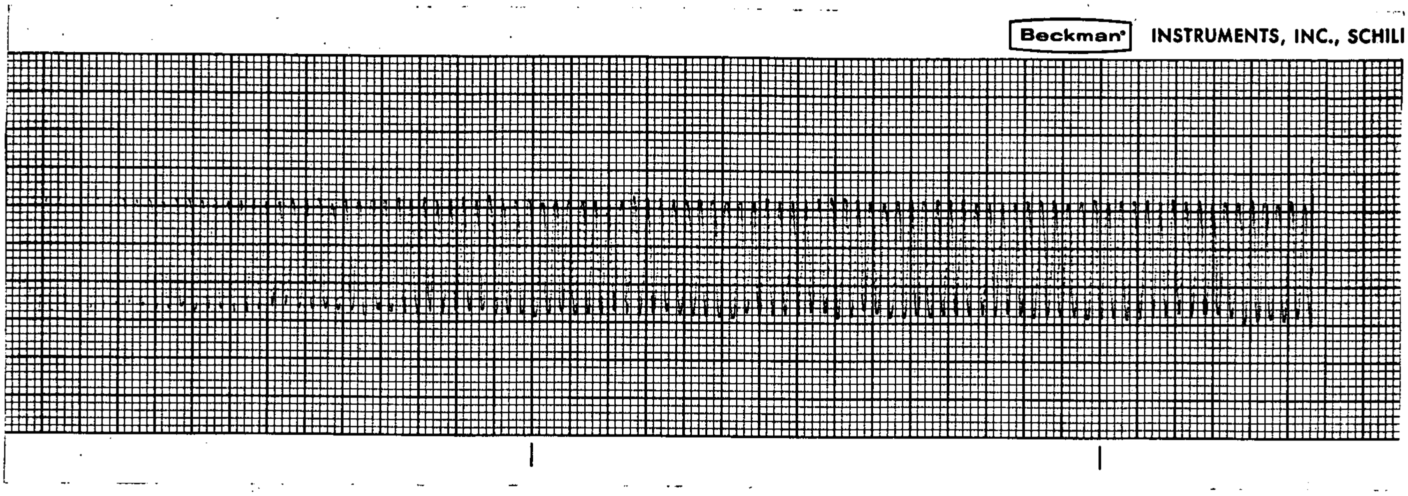


10 Hz signal 50 mm/sec; 1 v/cm

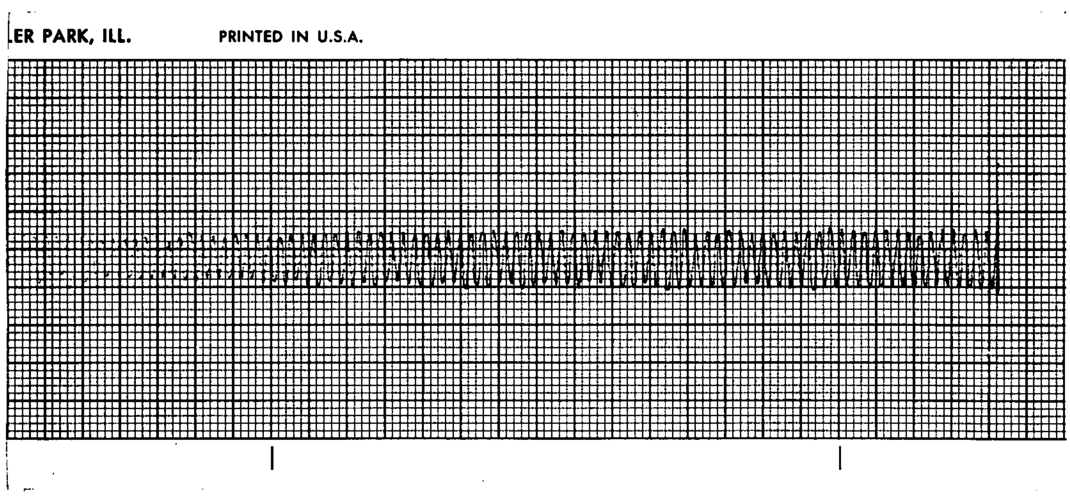


20 Hz signal 50 mm/sec; 1 v/cm

FIGURE 2.4-3

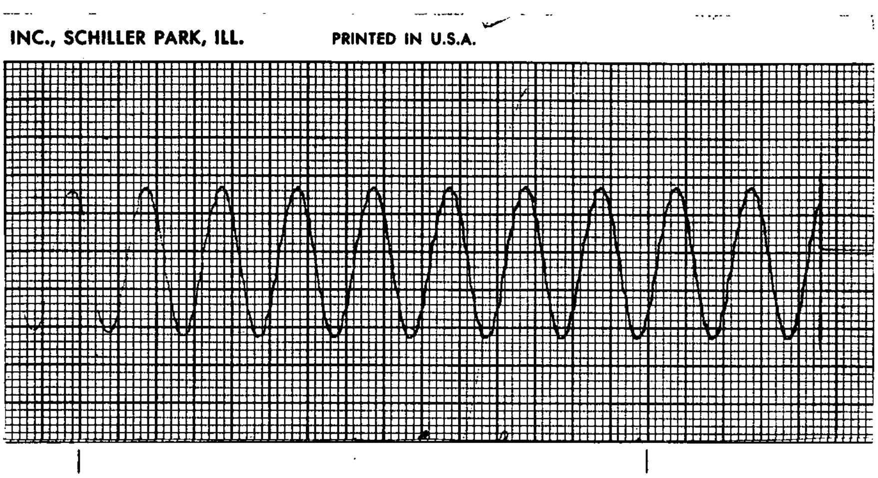


30 Hz signal 125 mm/sec; 1 v/cm



35 Hz signal 125 mm/sec; 1 v/cm

FIGURE 2.4-4



5 Hz signal   50 mm/sec; 1 v/cm

5 Hz signal from the signal generator fed directly into the recorder showing the 60 Hz problem to be in the recorder.

FIGURE 2.4-5

2.5 Telephone Coupler

There are two types of non-hardwire telephone couplers in normal use - magnetic and acoustic. With the acoustic coupler, the dominant distortion is from the mouthpiece associated with the characteristics of a pressure-operated carbon microphone. This type of microphone exhibits significant non-linear distortion, second-harmonic distortion, and also has inherent background noise. However, the high output level makes this type of microphone desirable from the telephone industry point of view. The limitations of the carbon microphone have minimum effect on voice transmission but do impose problems when used for data transmission. Conversely, the universality of the acoustic coupler is extremely attractive and for this reason was investigated first.

Exhaustive effort was expended in an attempt to perfect a technique which would render the acoustic coupler acceptable, but the distortion of the signal by the carbon microphone was too severe. The microphone's non-linearity generates sum and difference frequencies. Some of these extraneous signals are of the same frequency as the carriers. For example, subtracting the carrier frequency of Channel 4 from the sum of the frequencies of Channel 2 and 3, yield a frequency equal to that of Channel 1.

Channel 1	1322
Channel 2	1466 = 1322 + 144
Channel 3	1610 = 1322 + 2(144)
Channel 4	1754 = 1322 + 3(144)

$$1466 + 1610 - 1754 =$$
$$[1322 + 144] + [1322 + 2(144)] - [1322 + 3(144)] =$$
$$2(1322) + 3(144) - 1322 - 3(144) = 1322$$

Efforts to change the spacing of the lower channels (the noisest channels) did not improve the S/N ratio significantly. Experimentally, four channels could be coupled acoustically without degrading any single channel to an unacceptable level. An attempt at multiplexing two groups of four simultaneous channels was made. This approach was unsuccessful, primarily due to the inability of the speaker (or any electromechanical transducer) to make an instantaneous change from one series of signals to another series of signals, without ringing at its naturally resonant frequency.

Several feedback control systems were implemented and tested in an attempt to distort the signal in such a manner as to cancel the distortion caused by the carbon microphone. These were all unsuccessful.

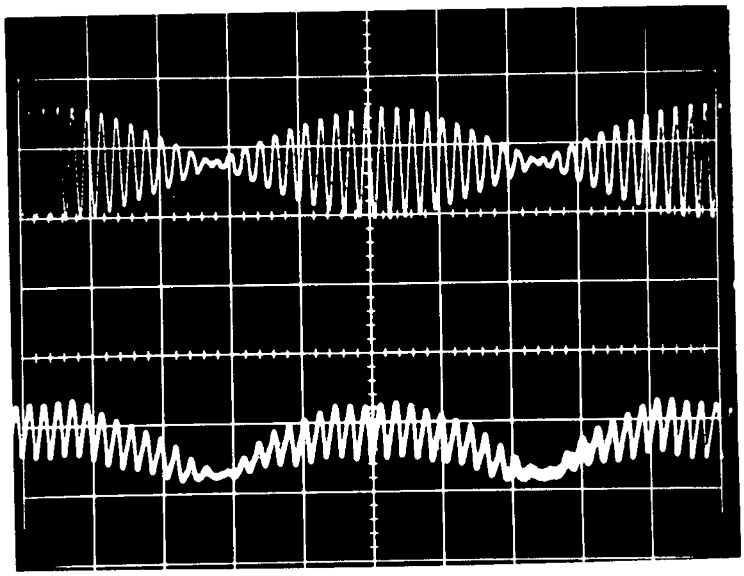
The acoustic coupler was also driven at different levels, seeking one for which the signal-to-distortion ratio would be maximized. No such level was found.

Also investigated were different methods for pre-emphasizing the eight carrier frequencies in an attempt to decrease the distortion; or, at least, to increase the S/N ratio on those channels requiring such, but again to no avail. Figure 2.5-1 is an example of the type of distortion introduced by the carbon microphone. The top trace shows the signal input to the acoustic coupler. The second shows the signal on the telephone line as reproduced by the carbon microphone. Figure 2.5-2 is an example of baseline noise at the lowest level ever achieved for the acoustic coupler.

Finally, the inductive coupler was investigated and, with comparatively little effort, a satisfactory system was constructed. With the inductive coupler, the signal reproduced on the telephone line is practically free of background noise (caused by the coupling) and second harmonic distortion. Also, the non-linear distortion is insignificant.

At the receiver, the output of the inductive coupler is much greater than that of the acoustic coupler (crystal or dynamic). This increased input signal relaxes the requirements of the input amplifier. Much less gain is required; thus, decoupling the amplifier from the eight difference frequency oscillators on the same card is less critical.

Input .2 v/cm

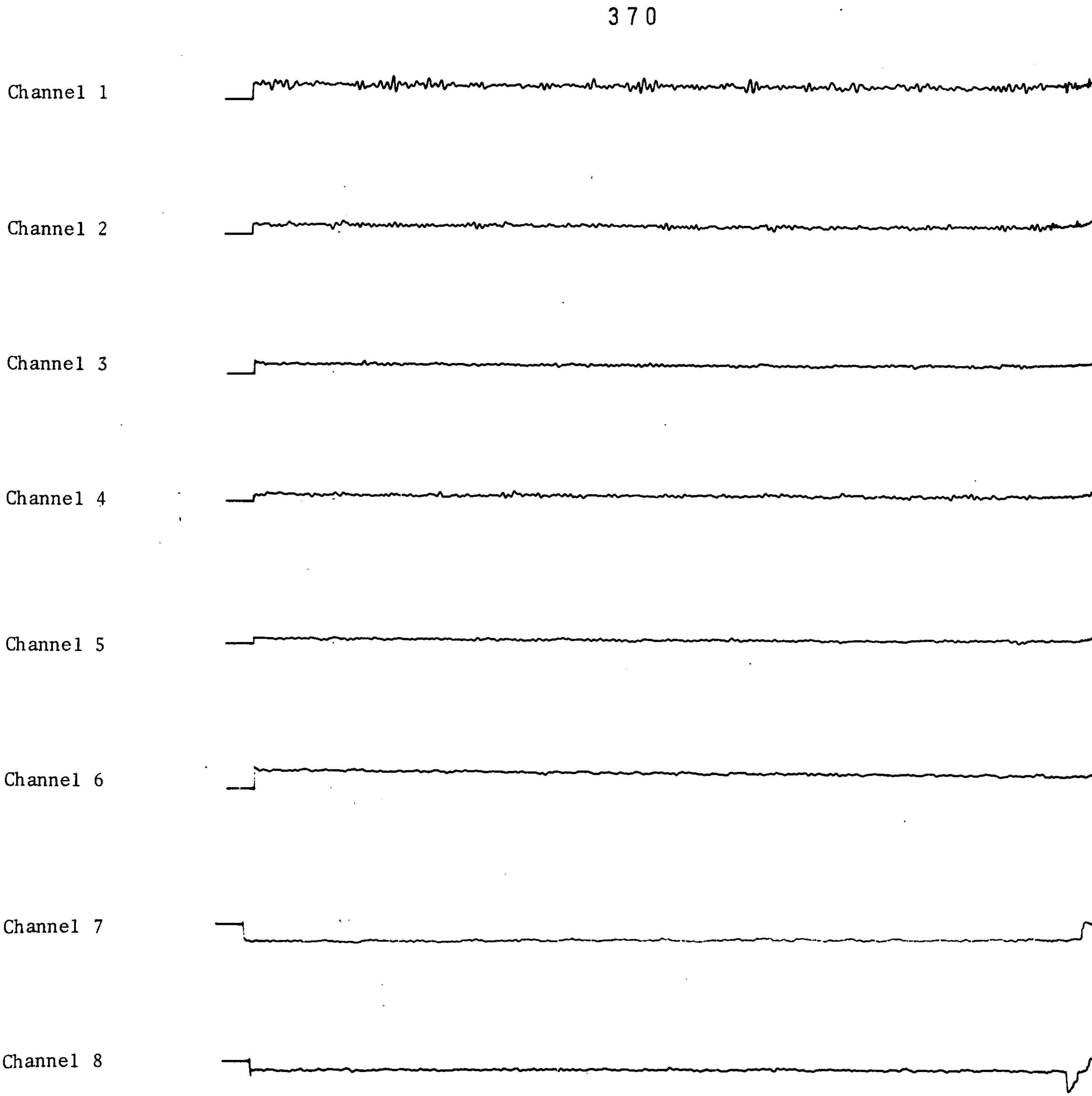


Output .5 v/cm

Horizontal - 2 ms/cm

The input to the acoustic coupler (top trace) is that obtained by summing the unmodulated VCO outputs of Channels 7 & 8. The output is the signal as reproduced on the telephone line by the carbon microphone.

FIGURE 2.5-1



Baseline Noise Acoustically Coupled

FIGURE 2.5-2

3.0 SYSTEM DESCRIPTIONS

3.1 Transmitter

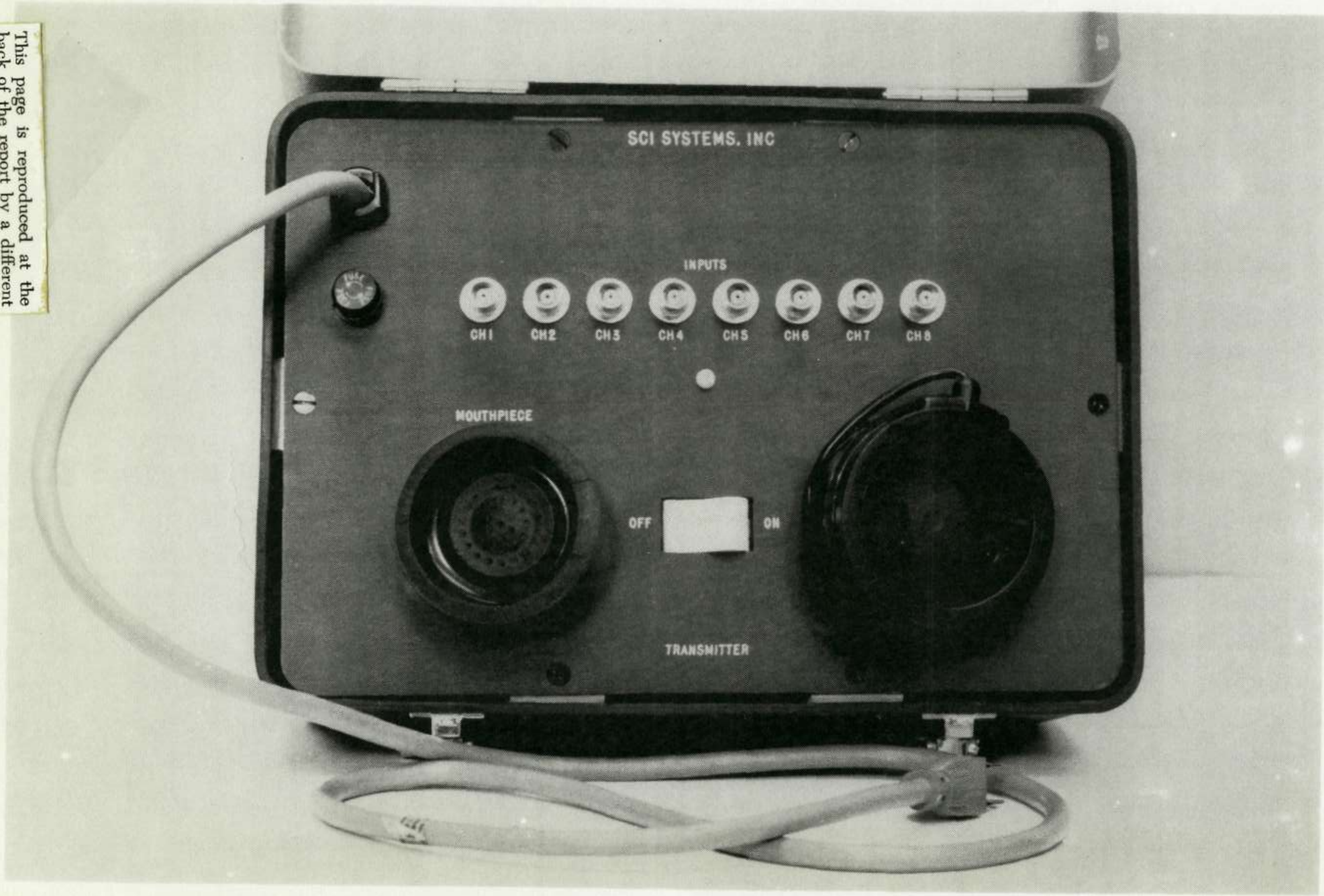
Figure 3.1-1 is a photograph of the front panel of the eight channel telephone telemetry transmitter developed under Contract NAS 9-12947. Figure 3.1-2 is a photograph showing the single electronics card, power supply, and wiring associated with the transmitter. The schematic diagram of the transmitter is shown in drawing number 601326 sheets 1 and 2. Since all eight channels are basically alike, only one channel (Channel 1) will be discussed.

The following discussion refers to drawing number 601326 Sheet 1. The modulating input to Channel 1 is capacitively coupled to the VCO input by capacitor C1, which determines the low frequency response of the system. Resistors R3 through R6 provide attenuation of the input while R2 establishes a means of adjusting the maximum deviation of the carrier. R4 through R7, as well as C3, together determine the center frequency of the carrier. They were chosen for high temperature stability. R5 is provided for adjusting the center frequency. The VCO is an LM566 integrated circuit voltage-controlled oscillator, with a triangular output on Pin 4. R8 and R9, with C4, provide some filtering of the triangular signal. Little filtering is needed, however, since only third harmonics are present and these are beyond the bandwidth of the telephone system.

Each of the eight channels is pre-emphasized; R9 pre-emphasizes Channel 1, R18 pre-emphasizes Channel 2, ..., R71 pre-emphasizes Channel 8. C10 is also a determining factor in the pre-emphasis scheme, which is necessary to produce equalization of the carrier amplitudes in the received signal. The carriers are then summed and capacitively coupled into the LM380 output amplifier. C10 blocks the DC current and resonates with the coupler at 2-KHz. This resonance is broad (being of low-Q) and therefore serves to increase the drive for all channels.

The inductive coupler is placed over the earpiece of the transmitting telephone.

This page is reproduced at the back of the report by a different reproduction method to provide better detail.

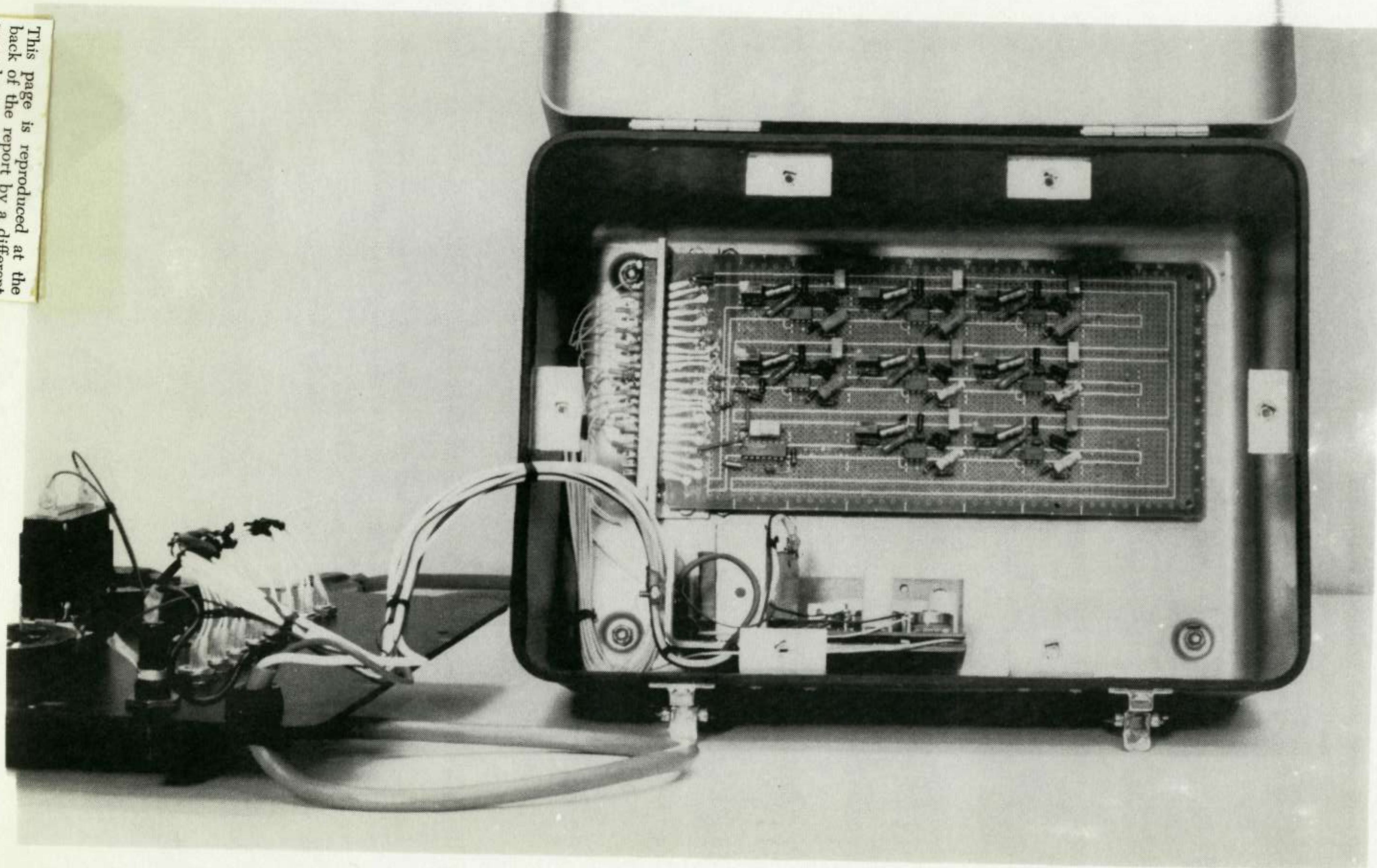


21

Eight Channel Telephone
Telemetry Transmitter

(Part No. 501441)

Figure 3.1-1

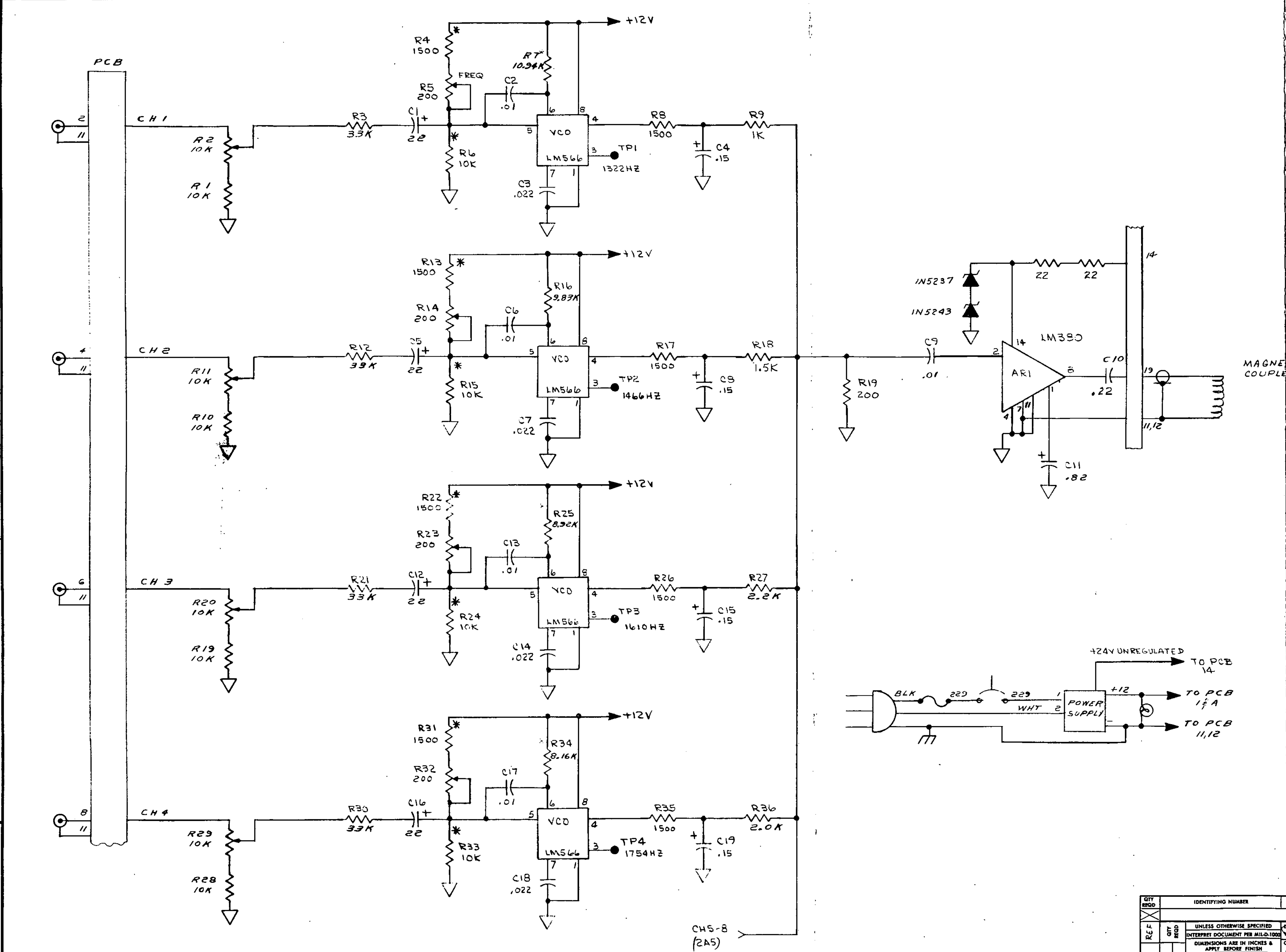


Eight Channel Telephone
Telemetry Transmitter
(Internal View)

Figure 3.1-2

FOLDOUT FRAME

REVISIONS				
LTR	DESCRIPTION	DATE	CHK	P/E D/C
X1	PRERELEASED	1/4/73		
X2	REV PER ENG MARKUP			
X3	CHANGED 1460HZ TO 1466HZ	2-5-73		



NOTES (UNLESS OTHERWISE SPECIFIED)

1. RESISTORS ARE IN OHMS, 1/4 W, 5%.
2. CAPACITORS ARE IN MICROFARADS, 20V.

REFERENCE DESIGNATORS	
LAST	NOT USED
R73	
C35	
AR1	
TP8	

SCHEMATIC DIAGRAM
TELEPHONE/TELEMETRY
TRANSMITTER

SIZE D | CODE IDENT NO. 17981 | 601326 | REV X3

SHEET 1 OF 2

DRAFTSMAN 10/17/72 — CHECKER 1/11/73 — PROJECT ENGINEER 1/11/73 — DOCUMENT CONTROL 1/12/73

UNLESS OTHERWISE SPECIFIED INTERPRET DOCUMENT PER MIL-D-1000. DIMENSIONS ARE IN INCHES & APPLY BEFORE FINISH. DEBURR & BREAK ALL EDGES. TOLERANCES: DRILLED HOLES PER AND 10387. FRACTIONS ± ANGLES ± DECIMALS (.X) ± .1 (.XX) ± .02 (.XXX) ± .010

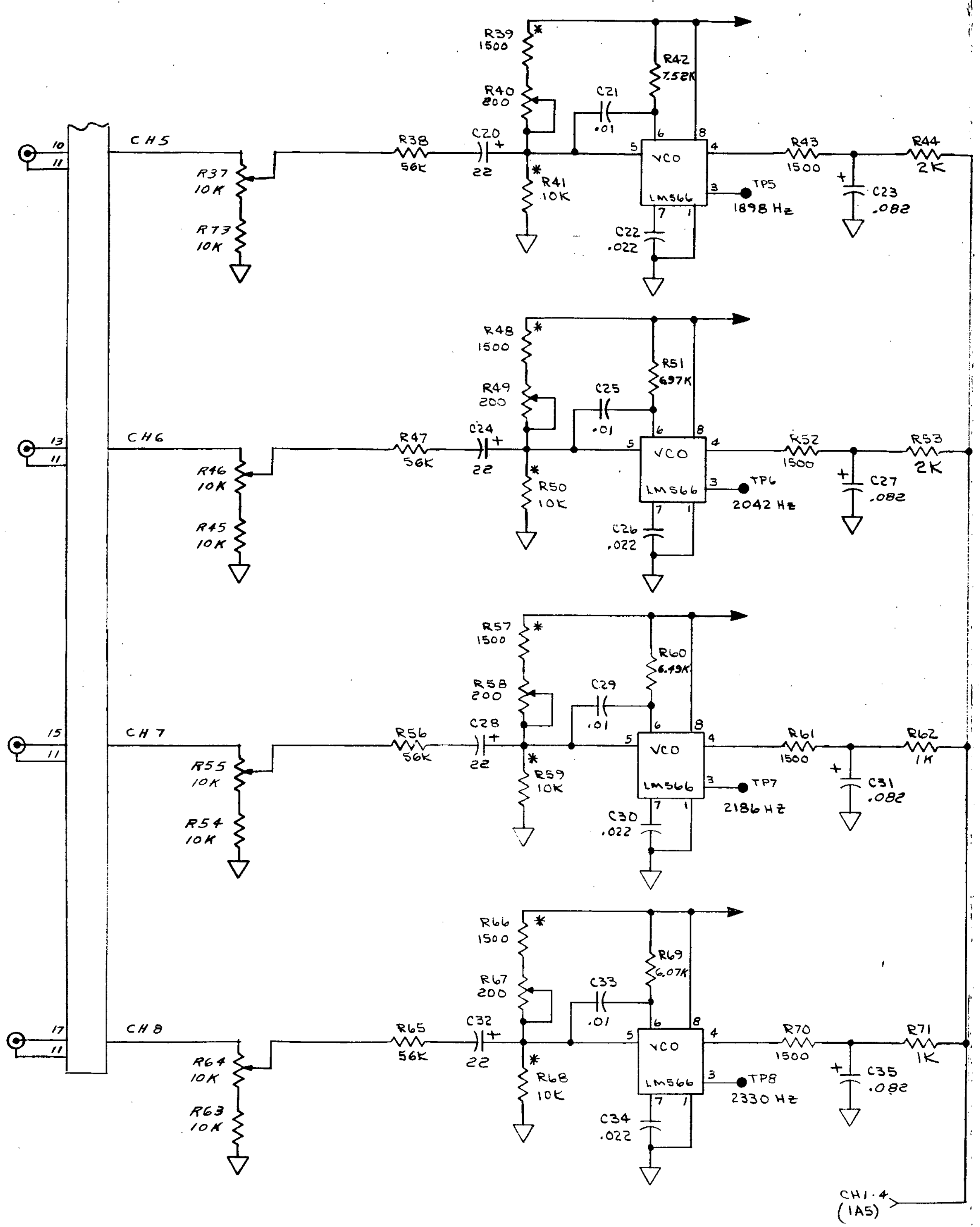
3262

FORM SCI-D-11 (3-71)

23

FOLDOUT FRAME

FOLDOUT FRAME



SIZE	CODE IDENT NO.		REV
D	17981	601326	X3
SCALE		UNIT WT.	SHEET 2

2H

601326

A

B

FORM SCI-D-5 (7-70)

3.2 Receiver

Figures 3.2-1 and 3.2-2 are photographs of the receiver showing the front panel and internal mechanical packaging, respectively. Drawing number 501435 is a block diagram of the receiver.

A schematic diagram of the input amplifier and oscillator card is shown in drawing number 601392. AR9 is a bandpass amplifier conditioning the input signal and driving the mixers of all eight channels. The remaining four cards are interchangeable having two channels per card.

The following discussion refers to drawing number 601324. The SN7490N's are configured in symmetrical divide by ten circuits. Together the two SN7490N's divide the incoming difference frequency from 9.8678 MHz to 98,678 Hz (for Channel 1). The output is attenuated to a level compatible with the high-level input of the first mixer (MC1496L). The composite signal amplified by AR9 is directed to the low-level mixer input and translated up by 98,678 Hz. Those frequency components 50-Hz either side of 1322-Hz are passed by the crystal bandpass filter (1322 + 98,678 = 100 KHz) and all others are rejected. The 98,678 Hz output is also routed back to the oscillator card where it is buffered by AR10 and directed to the high-level inputs of each of the second mixers of all eight channels. The output of the crystal bandpass filter is then directed to the low-level input of the second mixer for translation to 1322 ± 50 Hz (100 KHz - 98,678 Hz = 1322 Hz).

The FM signal is then demodulated by the LM565 Phase-locked loop, amplified by AR2 and filtered by AR3 and AR4, thereby setting the upper frequency of the system bandwidth to 30-Hz.

Eight Channel Telephone
Telemetry Receiver

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(Part No. 501442)

Figure 3.2-1

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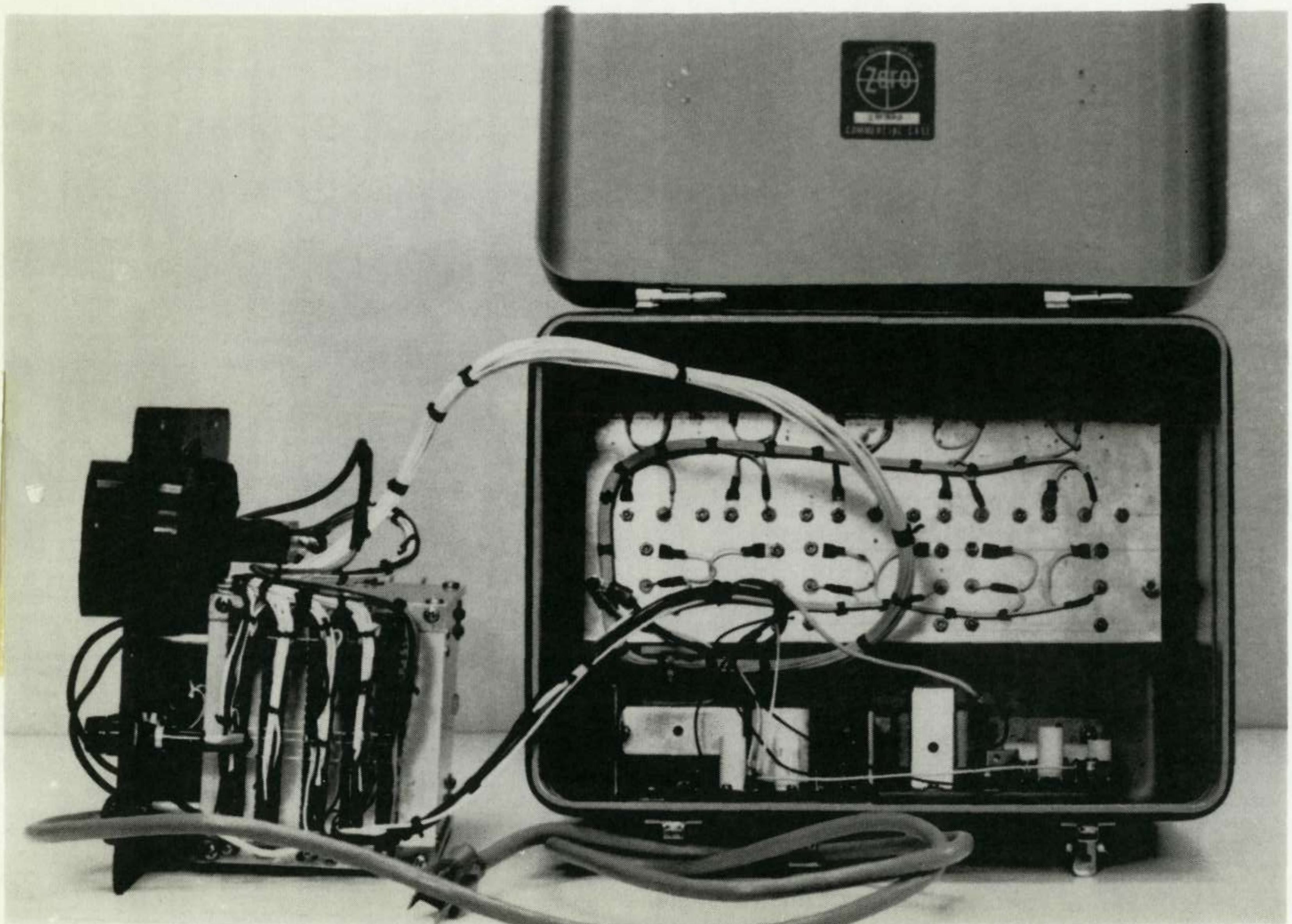


Eight Channel Telephone
Telemetry Receiver
(Internal View)

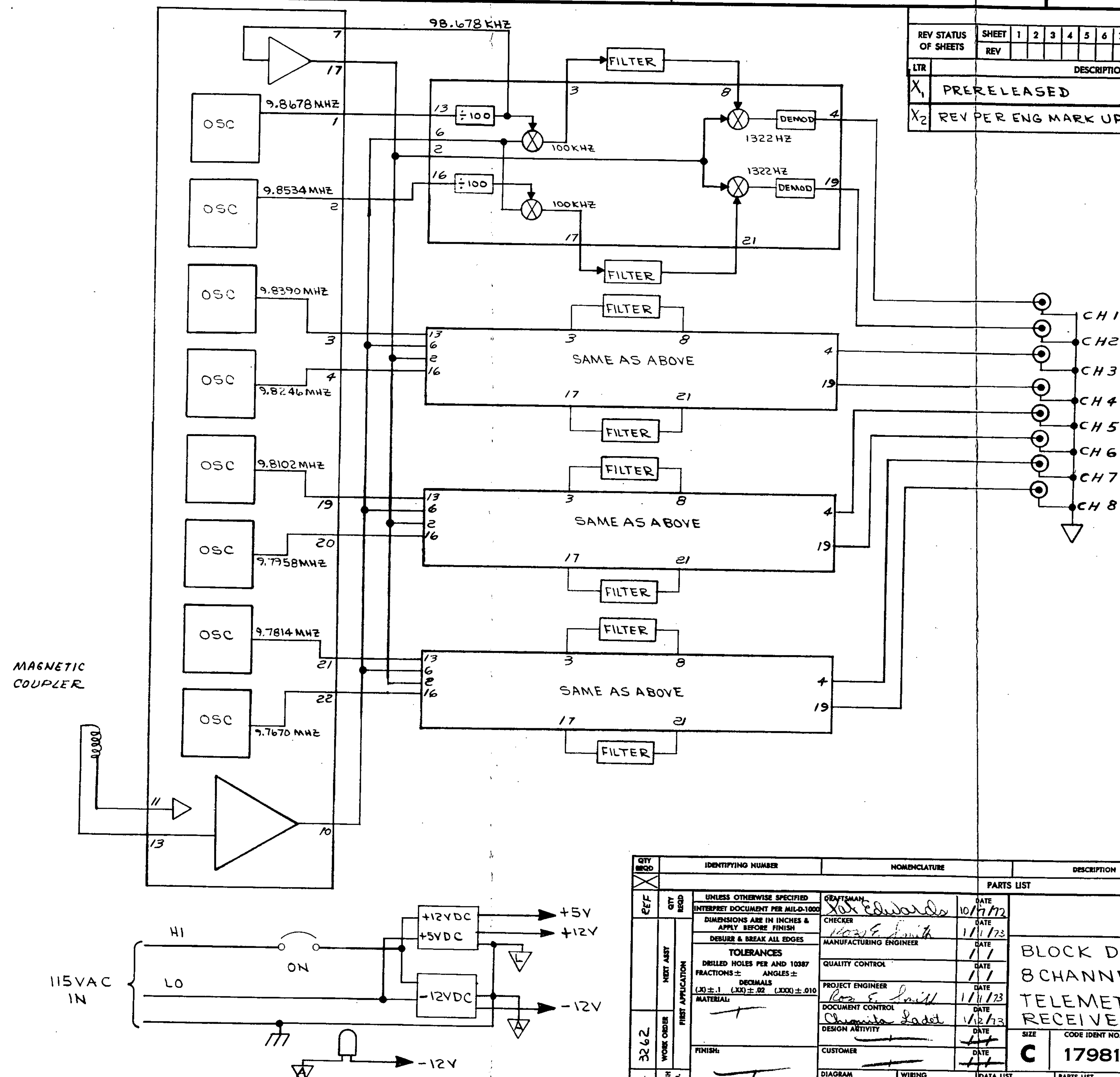
27

Figure 3.2-2

FOLDOUT FRAME

FOLDOUT FRAME

REVISIONS					
LTR	DESCRIPTION	DATE	CHK	P/E	D/C
X_1	PRERELEASED	1/11/73			
X_2	REV PER ENG MARK UP.				



PARTS LIST

UNLESS OTHERWISE SPECIFIED INTERPRET DOCUMENT PER MIL-D-1000
DIMENSIONS ARE IN INCHES & APPLY BEFORE FINISH
DEBURR & BREAK ALL EDGES
TOLERANCES
DRILLED HOLES PER AND 10387
FRACTIONS ± ANGLES ±
DECIMALS
(.X) ± .1 (.XX) ± .02 (.XXX) ± .010

DRAFTSMAN	Edwards	10/17/72
CHECKER	Smith	1/11/73
PROJECT ENGINEER	Smith	1/11/73
DOCUMENT CONTROL	Chiquita Ladd	1/12/73

EFF 3262

BLOCK DIAGRAM
8 CHANNEL TELEPHONE / TELEMETRY SYSTEM RECEIVER

SIZE C | CODE IDENT NO. 17981 | 501435 | REV X_2

SHEET 1 OF 1

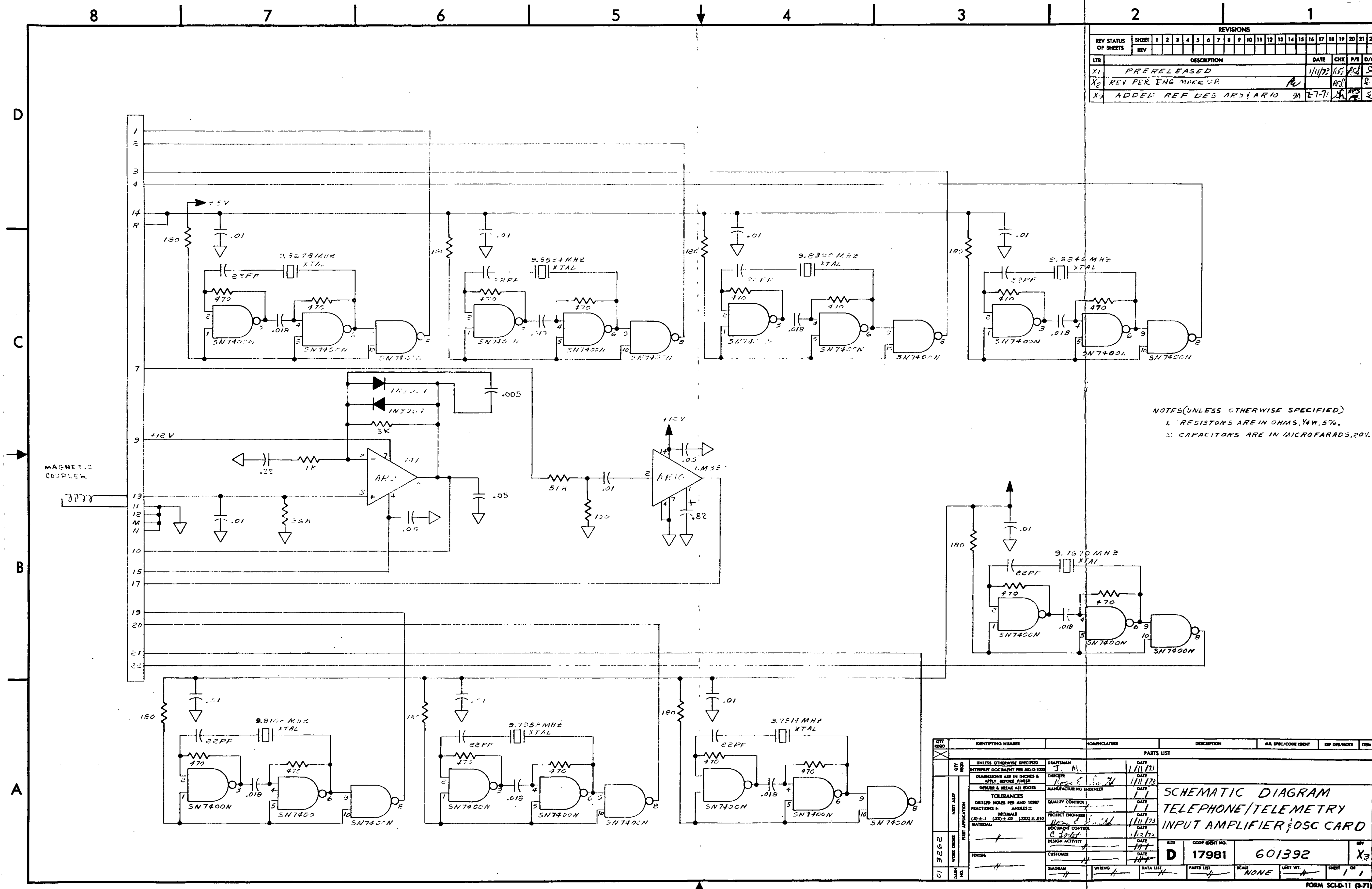
FORM SCI-810-041 (3-71)

501435

28

FOLDOUT FRAME

FOLDOUT FRAME

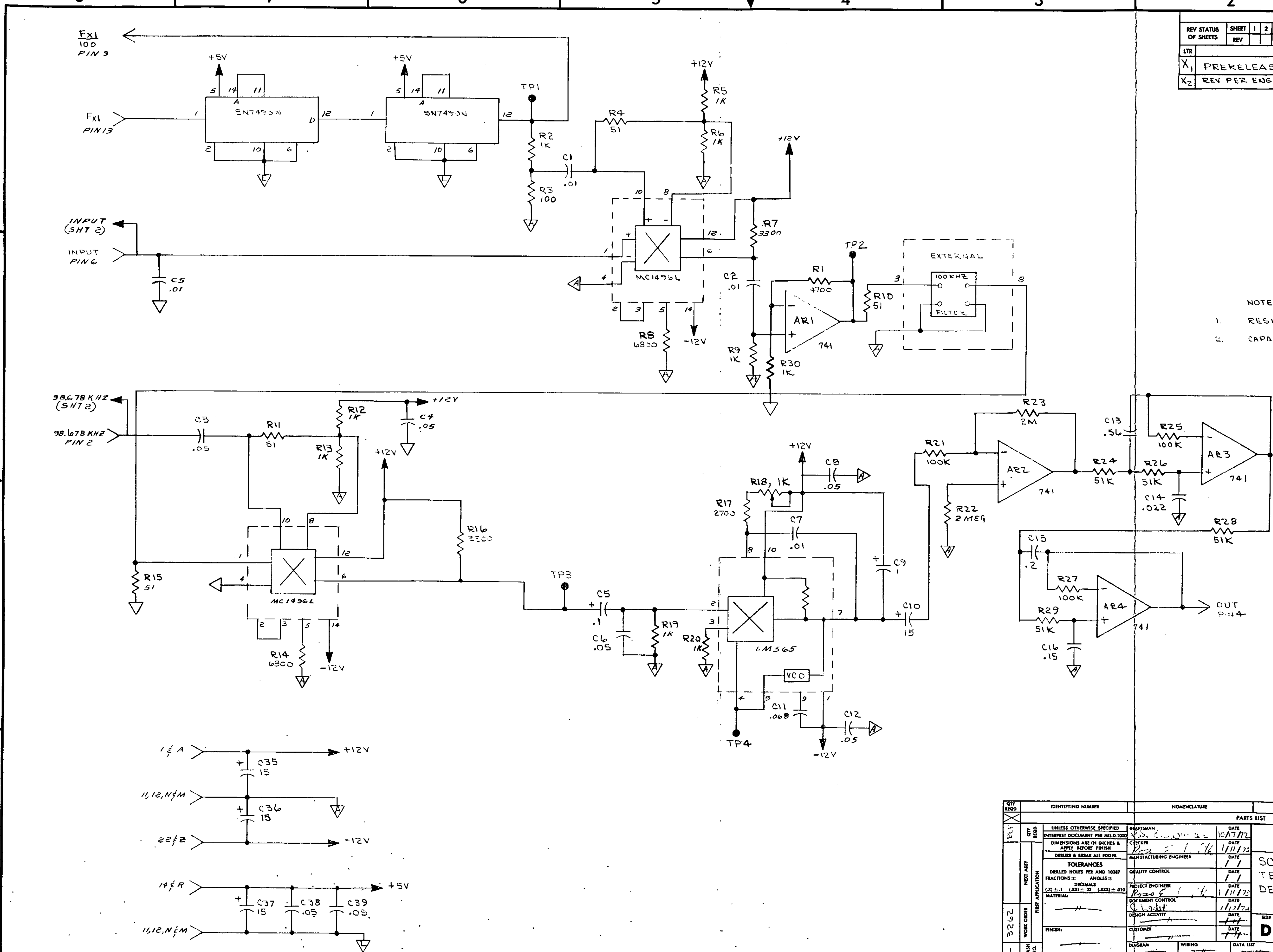


29

FOLDOUT FRAME

FOLDOUT FRAME

REVISIONS				
LTR	DESCRIPTION	DATE	CHK	P/E
X_1	PRERELEASED	11/1/73		
X_2	REV PER ENG MARK-UP			



NOTES (UNLESS OTHERWISE SPECIFIED)

1. RESISTORS ARE IN OHMS, 1/4 W, 5%.
2. CAPACITORS ARE IN MICROFARADS, 20V.

REFERENCE DESIGNATORS	
LAST	NOT USED
R62	
C40	
AR8	
Z	
TP8	

SCHEMATIC DIAGRAM
TELEPHONE / TELEMETRY
DEMODULATOR

SIZE D CODE IDENT NO. 17981 601324 REV X_2

SHEET 1 OF 2

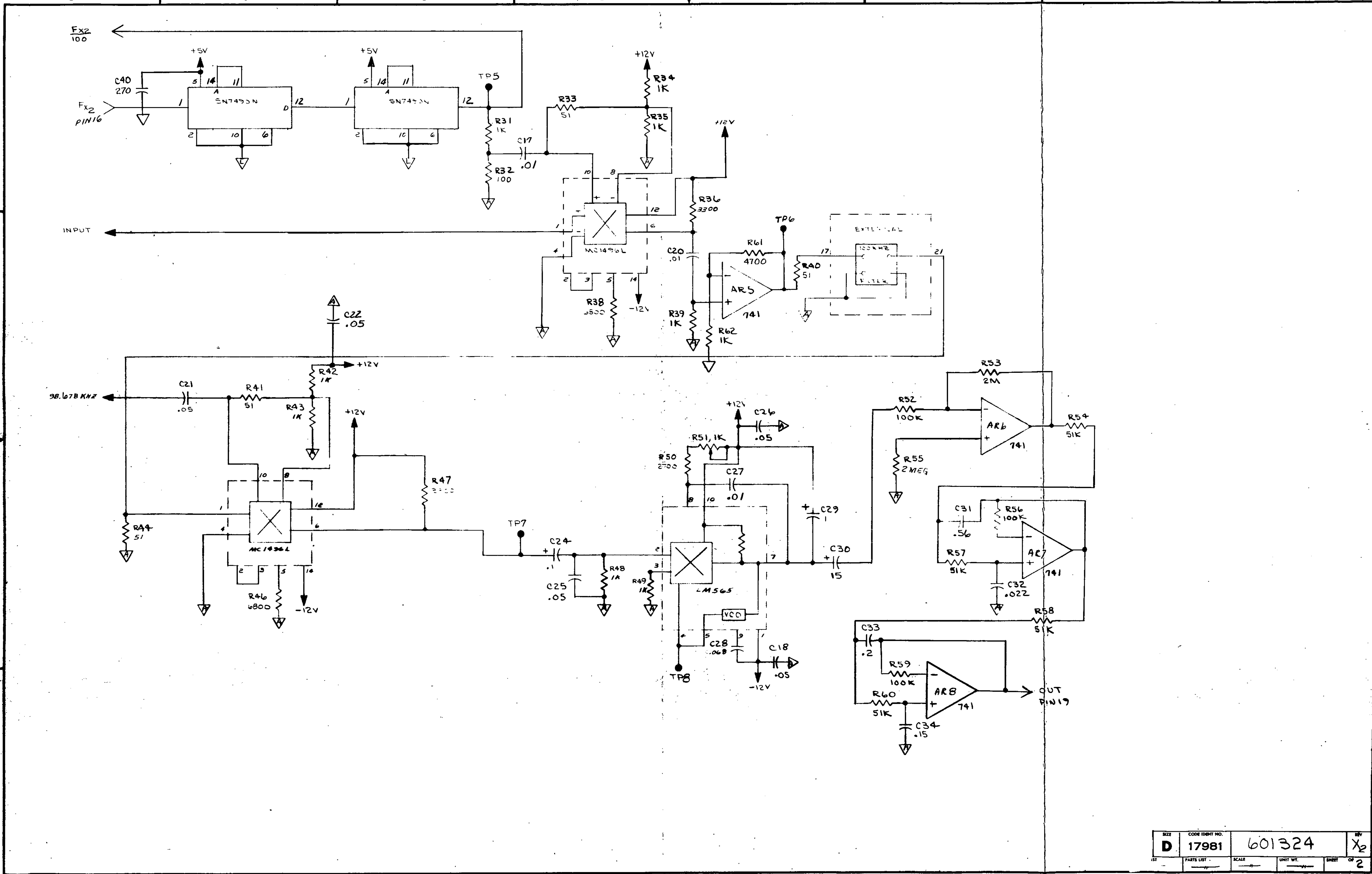
WORK ORDER 3262

FORM SCI-D-11 (3-71)

30

FOLDOUT FRAME

FOLDOUT FRAME



D 17981 601324 X2

2

FORM SCI-D-11 (3-71)

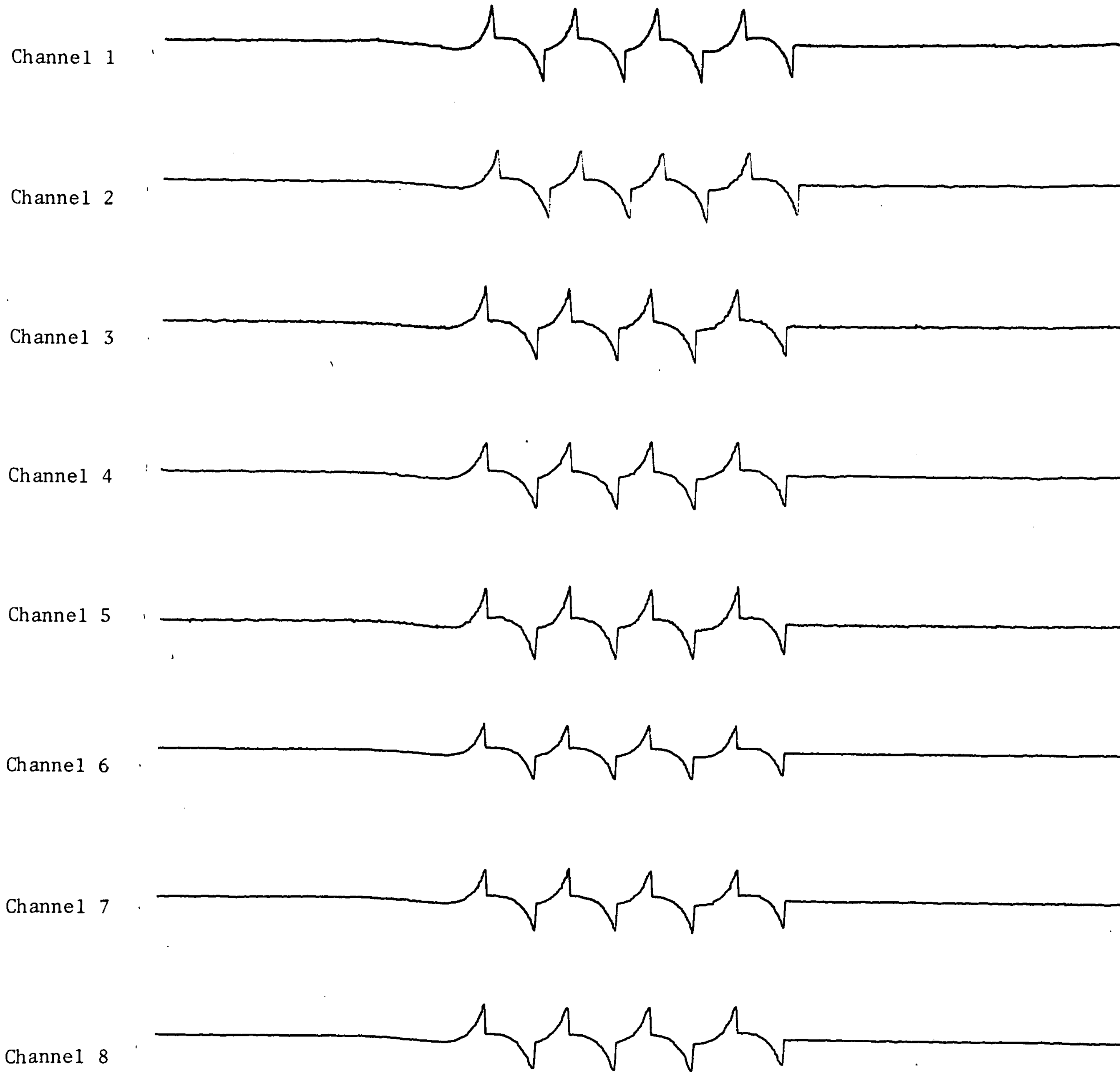
31

4.0 TEST RESULTS

Clinical testing of the system was performed at the Methodist Hospital Neurophysiology Laboratory. One telephone extension was used to obtain an outside line and to call another extension in the laboratory. In this manner, a telephone link was established which was routed through the hospital switchboard twice and through one Houston exchange. It was immediately evident when conversing via this link, that the level of the voice (and also the signal) was reduced as compared to conversation via a connection originating outside the hospital. This was a desirable condition for testing purposes since it provided a below average telephone connection in order to demonstrate that the system could operate well under such conditions. In Figure 4.0-1 is shown representative baseline noise and a series of calibration signals reproduced by the system while inductively coupled to the telephone over the connection described above. Figure 4.0-2 is an example of a received EEG signal to be compared with the original signal in Figure 4.0-3.

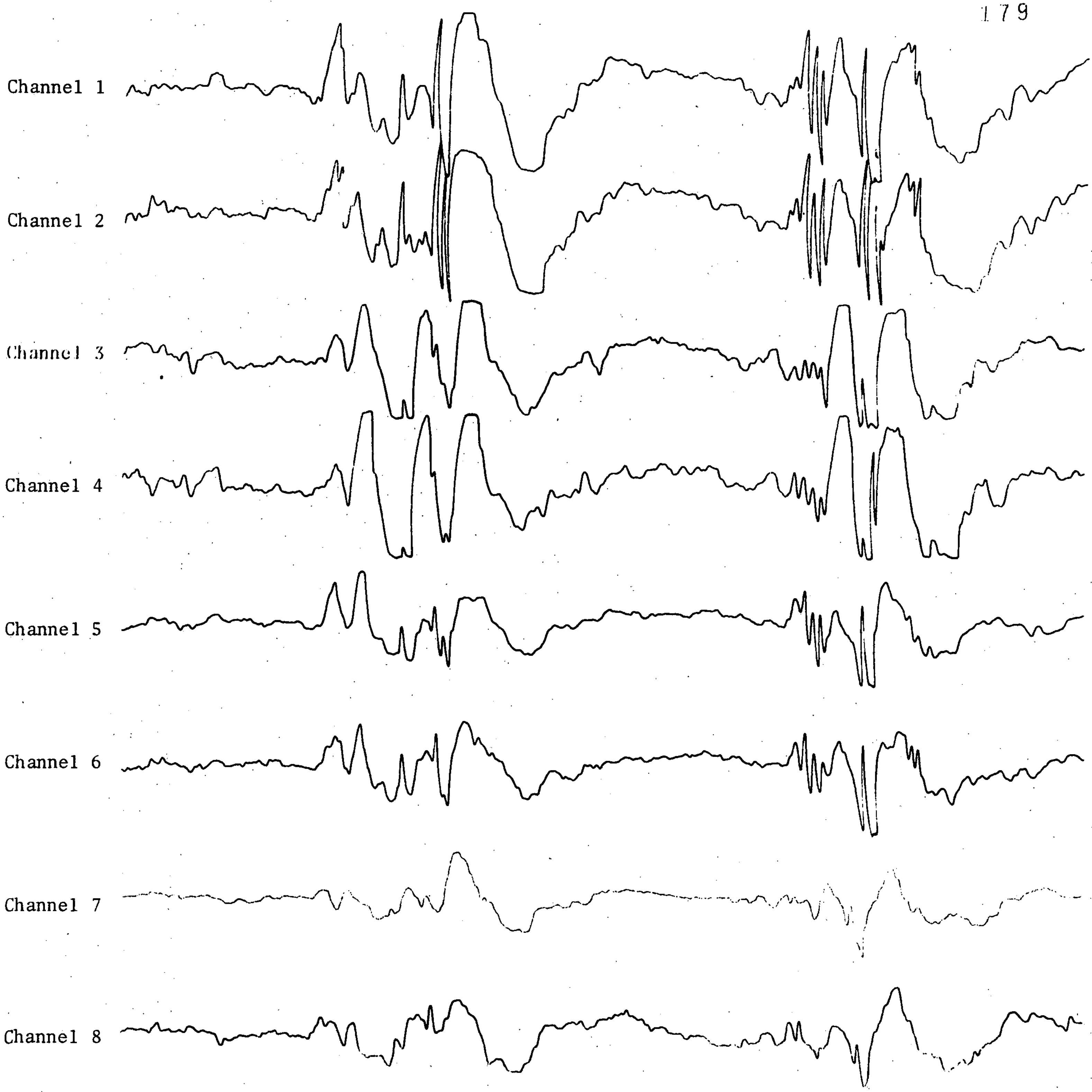
In Figure 4.0-4 is shown the simultaneous outputs of all eight channels as they were sequentially modulated with a 1-Hz signal. It is evident that the crosstalk between channels is negligible.

The frequency response of the system is shown in Figure 4.0-5. All eight channels were modulated simultaneously. The frequency response of the Channel 4 recorder was not sufficient to show the response of the system. These data were obtained via a telephone link.



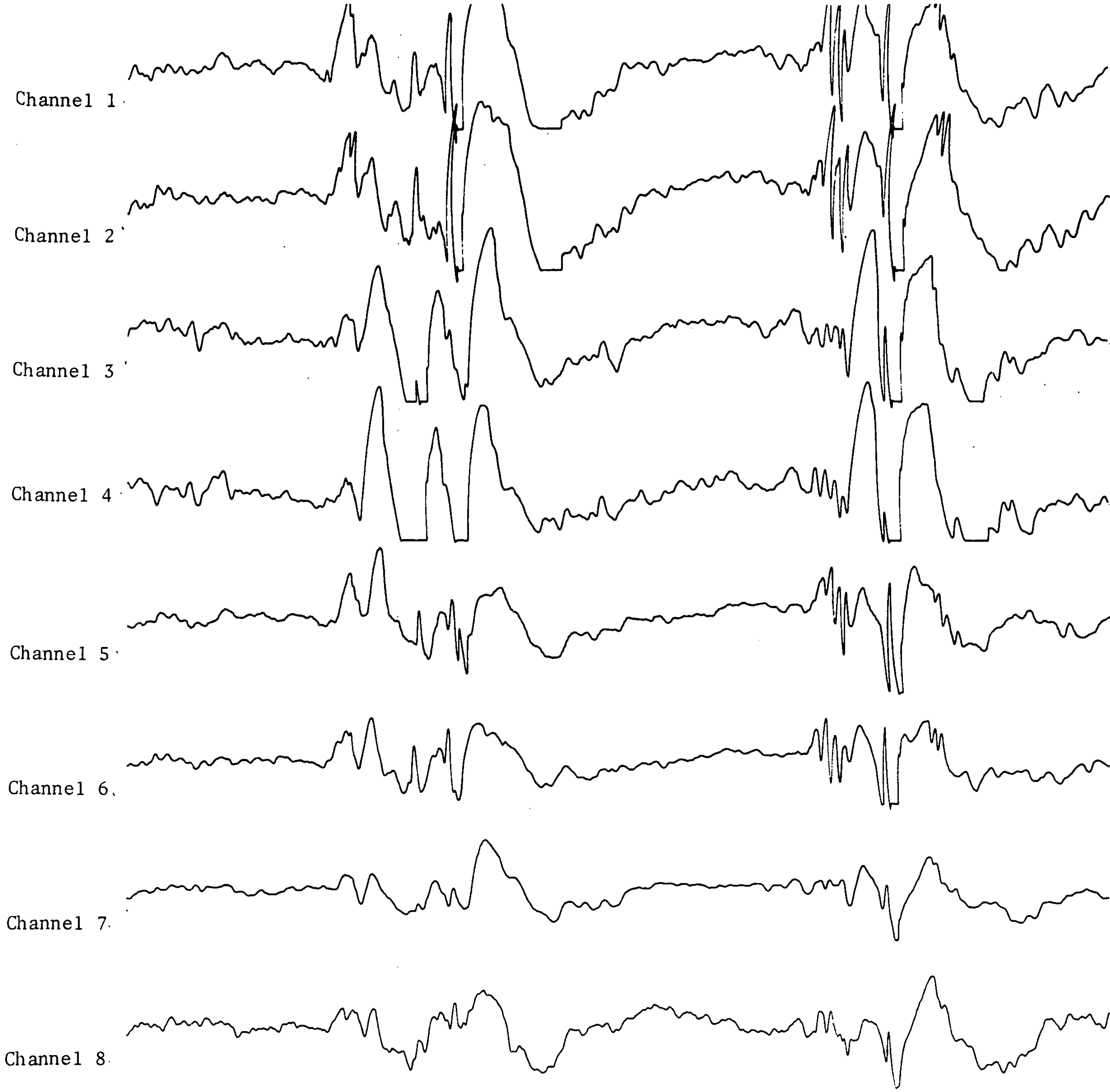
Received Calibration Signals

FIGURE 4.0-1



Reproduced Signal Inductively Coupled

FIGURE 4.0-2

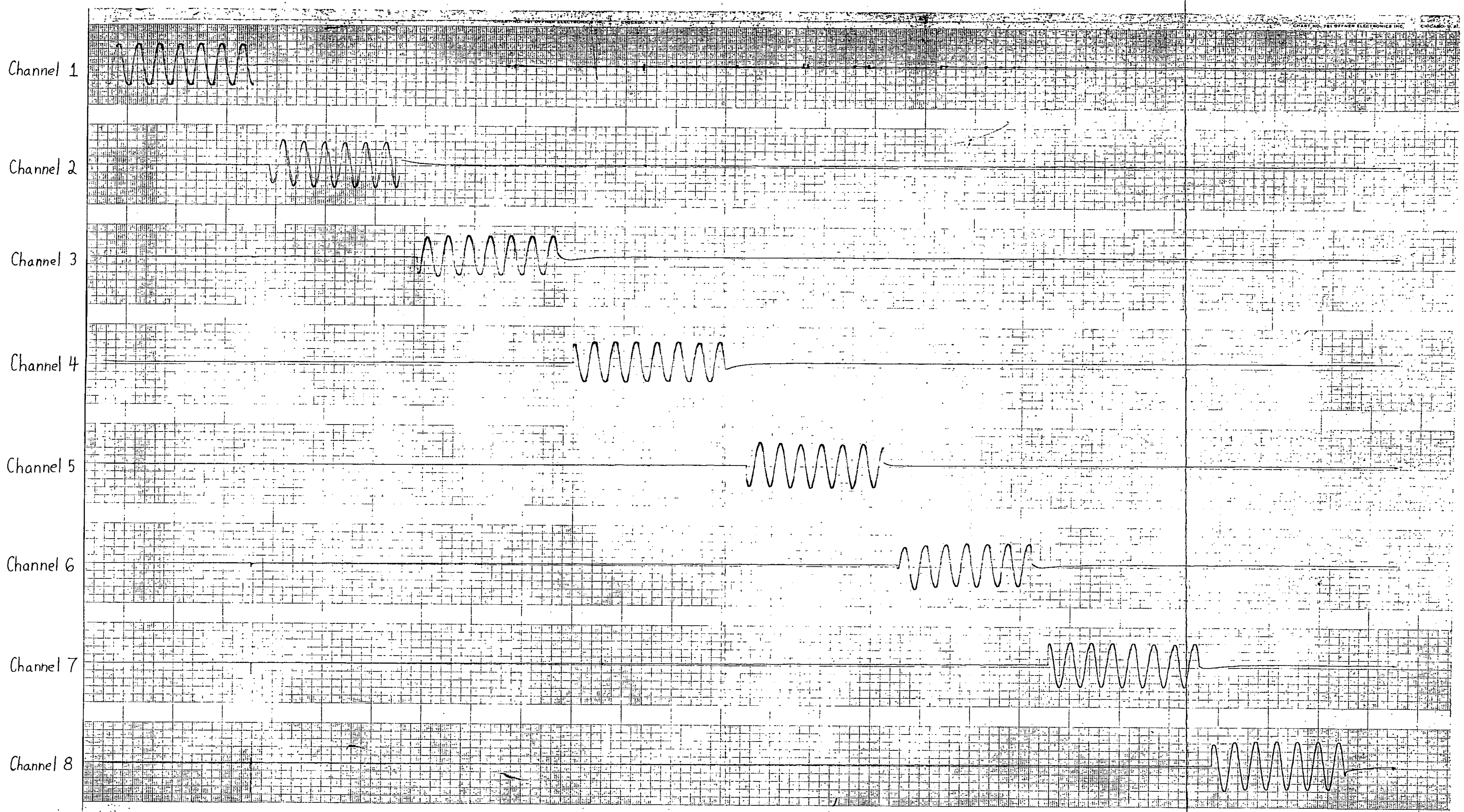


Transmitted Signal

FIGURE 4.0-3

FOLDOUT FRAME

FOLDOUT FRAME



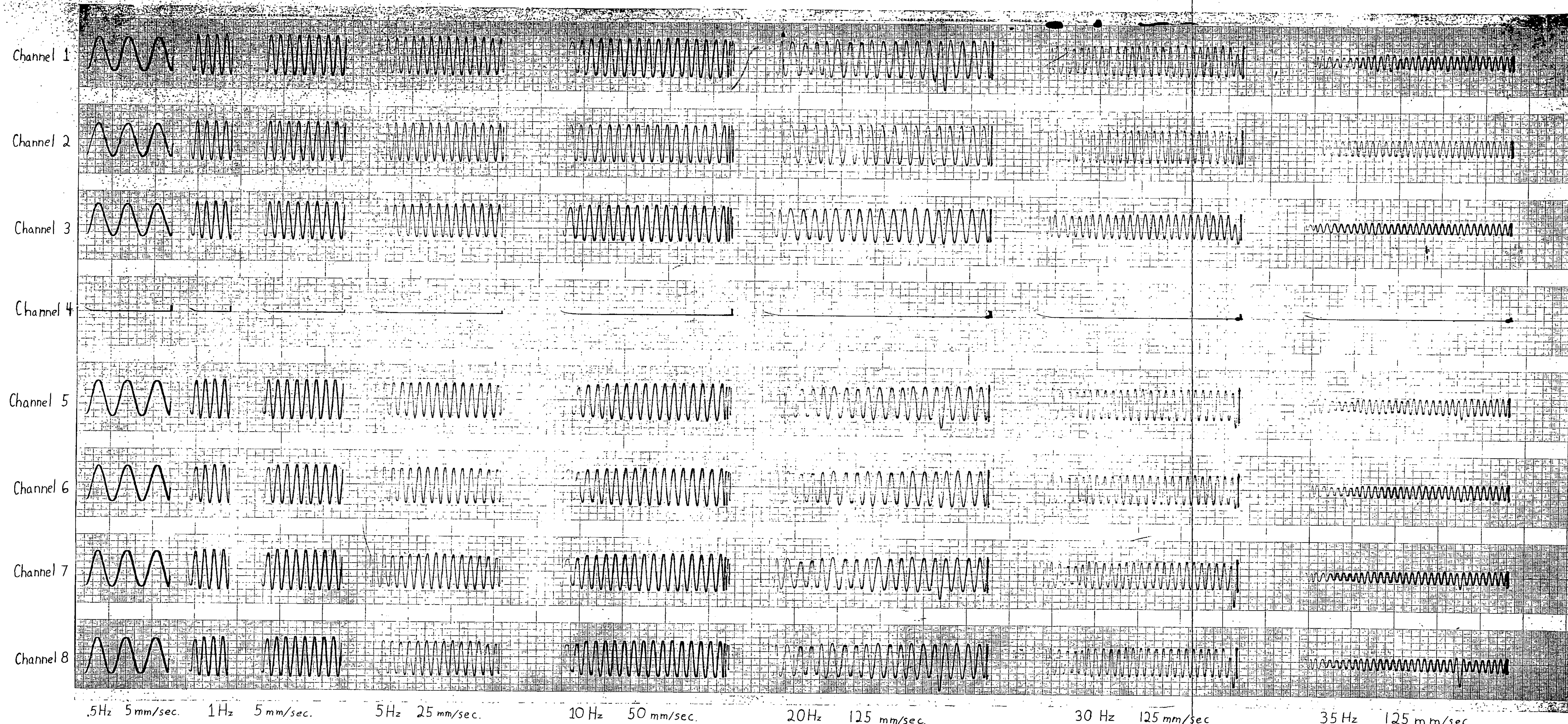
Crosstalk

Figure 4.0-4

A

B

FOLDOUT FRAME



(all deflections 1v/cm.)

Frequency Response of the Eight Channel Telephone Telemetry System

Figure 4.0-5

A

B

5.0 CONCLUSION

The eight channel prototype telephone telemetry system described in this report was successfully designed, constructed, tested, and delivered to NASA/MSC. All objectives of the program and requirements of the Statement of Work have been completed.