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COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE— Design of a Modified Raised Cosine Filter Using Hybrid Integrated Filter Sections

MM 67 – 5316 – 6

CASE CHARGED— 38763

FILING CASES— 38763-17

DATE— September 14, 1967

AUTHOR— M. S. Lane

FILING SUBJECTS— Active Filters
Hybrid Integrated Circuit

ABSTRACT

Synthesis of a modified raised cosine filter using hybrid integrated filter sections consisting of tantalum thin film RC networks and monolithic silicon integrated operational amplifiers is examined. The filter function is derived from a discrete passive RLC filter and the filter is realized by a cascade of first and second order active networks. The filter was built and tested; the results show that the active filter meets the specifications for the passive filter. This memorandum describes the derivation and synthesis of this filter and also includes the results of the measurements made on this active filter. The work described in this memorandum was done by the author while on a Graduate Study Program rotational assignment in Department 5316.

51

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BELL TELEPHONE LABORATORIES
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SUBJECT: Design of a Modified Raised Cosine Filter Using Hybrid Integrated Filter Sections
Case 38763-17

DATE: September 14, 1967

FROM: M. S. Lane

MM67-5316-6

MEMORANDUM FOR FILE

Introduction

Filters with modified raised cosine response find wide use in data communication systems. One such application is in the receiver of the 304 Data Set. In order to reduce the relatively large proportion of the overall equipment volume of the 304 Data Set occupied by the use of passive RLC filters, a modified raised cosine filter was designed using hybrid integrated filter sections consisting of tantalum thin film RC networks and monolithic silicon integrated operational amplifiers.

The filter design is based on the passive RLC modified raised cosine filter shown in Figure 1. The design procedure used is to determine a transfer function from this network using the IBM 7094 and network synthesis techniques. Then the filter transfer function is broken up into a product of first and second order transfer functions. These are then realized using a basic second order filter section.

The basic second order filter section used is the "Active RC Filter Building Block using Frequency Emphasizing Networks" described by G. S. Moschytz.[1] This network offers the economical advantages of circuit standardization and the advantages of a low sensitivity network. The building blocks also possess inherent isolating characteristics so that there is negligible interaction between them.

This memorandum describes the derivation of the transfer function of the modified raised cosine filter and the application of the second order building blocks to realize this transfer function.

Modified Raised Cosine Function

The in-band amplitude-frequency characteristic of a f_o kilo-bit modified full raised-cosine roll-off filter is:

$$W(f) = \frac{\left(\frac{\pi f}{f_o}\right)}{\sin\left(\frac{\pi f}{f_o}\right)} \cos\left[\frac{\pi f}{2f_o}\right], \qquad 0 < f < f_o \text{ KHz}$$

Using trigonometric identities, this function is reduced to:

$$W(f) = \left(\frac{\pi f}{2f_o}\right) \cdot \cot\left(\frac{\pi f}{2f_o}\right), \qquad 0 < f < f_o \text{ KHz}$$

The in-band and out-of-band specifications for a 36 KB modified full raised cosine roll-off filter for the 304 Data Set are given in Figure 2.

Transfer Function

With frequency scaling from 40.8 kHz to 36 kHz, the S-plane plots in Figures 3 and 4 will have a transfer function which satisfies the specifications for the modified full raised cosine roll-off filter. These S-plane plots are derived by determining the transfer function of the 40.8 KB RLC filter in Figure 1 and then using the IBM 7094 to modify this transfer function.

The RLC filter in Figure 1 consists of four "constant-resistance" sections in cascade. Because of the "constant-resistance" property, the loaded transfer function of this RLC filter is the product of the loaded transfer functions of the cascaded constant-resistance sections.

$$T(s) = T_1(s) \cdot T_2(s) \cdot T_3(s) \cdot T_4(s)$$

For ease in determining the transfer function of these sections, the mutual inductance in the second and fourth sections is converted into an equivalent inductance. The resulting second and fourth section of the filter are then converted to simple lattice networks using the conversion techniques given in Appendix A. The application of impedance normalization and frequency scaling then results in the network shown in Figure 5.

The loaded transfer function of the first section in Figure 5 is determined from the network schematic using the IBM 7094.[2] This transfer function is:

$$T_1(s) = \frac{.7197(10^{-2})s^4 + .1896s^2 + 1.0}{.03525s^5 + .2396s^4 + .8112s^3 + 1.7403s^2 + 2.333s + 2.0}, \quad f_o = 40.8$$

The loaded transfer functions for a symmetrical lattice and for a bridge-tee are calculated in Appendix B and Appendix C, respectively. Applying the results of these calculations, the loaded transfer functions for the second, third, and fourth sections in Figure 5 are:

$$T_2(s) = \frac{-1\,(s-1.081)}{(s+1.081)}, \quad f_o = 40.8$$

$$T_3(s) = \left[\frac{.2130s^3+.8816s^2+1.3479s+2.8501}{.3941s^3+.9627s^2+2.3534s+3.3003}\right], \quad f_o = 40.8$$

$$T_4(s) = \left[\frac{s^2-1.750s+2.360}{s^2+1.750s+2.360}\right], \quad f_o = 40.8$$

The poles and zeroes of the transfer function of the passive RLC filter are determined by factoring the polynominals of the preceding transfer functions on the GE computer.[3] A study of these poles and zeroes shows that the second and fourth sections are nonminimum phase all-pass sections while the first and third sections are minimum phase sections which determine the amplitude response of the filter. S-plane plots of the nonminimum phase sections and of the minimum phase sections are given in Figures 6 and 7.

The closeness of some poles & zeroes in Figure 7 indicated it might be possible to cancel them. Using the s-plane plot of the minimum phase sections as a basis, additional s-plane plots with an acceptable amplitude response function are calculated on the IBM 7094.[4] The resulting simplified s-plane plot for the minimum phase portion of the response function is shown in Figure 4. Minimum phase functions which meet amplitude response requirements will also meet phase requirements; therefore, there is no need to alter the transfer function of the all-pass sections. The final s-plane plots shown in Figures 3 and 4 are used as the basis for the synthesis of the hybrid integrated filter.

Synthesis Techniques

The use of hybrid integrated circuits dictates constraints on the filter design in addition to the system specifications in Figure 2. Additional factors, which must be considered, are:

A. Sensitivity
B. Stability
C. Signal Level
D. Impedance Level
E. Size
F. Power Supply Voltage
G. Power Dissipation
H. Component Values

A synthesis system for development of multipole active RC networks using less sensitive two-pole networks is used because network sensitivity increases rapidly with the order of the network. Also, active linear networks are potentially unstable inasmuch as their transmission poles are not inherently constrained from crossing the jw-axis into the right-half plane. Thus, higher order networks are more difficult to stabilize.[5] It has become common practice in active filter design to realize any given Nth order transmission function by a cascade of first and second order networks, building blocks. For ease of implementation it is desirable that these building blocks possess inherent isolating characteristics so that there is negligible interaction between them.[1]

The design of a second order hybrid integrated filter building block consisting of tantalum thin film RC networks and semiconductor operational amplifiers has been performed by Department 5316. This building block, shown in Figure 8, contains two stabilized operational amplifiers, a twin-T network, and an RC filter network. Use of this building block takes advantage of the work already done by Department 5316 to stabilize and desensitize it; plus it has inherent isolating characteristics so that there is negligible interaction between building blocks in cascade.[5] Additional parameters considered in the use of the building block are given in Figure 9.

Using the building block with some modifications, a variety of synthesis techniques for second order networks is available. Second order transfer functions with their poles and zeroes in the left-half plane are realized using the frequency emphasizing networks shown in Figures 10 and 11.[1] First and second order all pass filter sections are available using the networks shown in Figures 12 and 13.* Second order transfer functions with poles in the left-half plane and zeroes on the jw-axis are realized using the frequency

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*These configurations were suggested by W. Thelen.

rejection network in Figure 14.[1] Additional synthesis techniques applicable to the building block are shown in Figure 15.[8] But these synthesis techniques are only applicable provided the calculated component values are within the range specified for the building block.

Filter Network

The Nth order transfer function of the s-plane plots in Figures 3 and 4 is realized by a cascade of first and second order networks. For low sensitivity, the transfer function is decomposed in Figures 16 and 17 into a product of second order functions whose complex poles are associated with zeroes in such a way that the distance from the upper half plane complex pole to the respective zeroes are made as far self-distant for each sub-network as possible.[6] The resulting 40.8 KB and normalized first and second order transfer functions for the nonminimum phase sections are:

$$T_2(s) = \left[\frac{s^2-1.7544(10^5)s+2.3602(10^{10})}{s^2+1.7544(10^5)s+2.3602(10^{10})}\right] \quad , f_o = 40.8$$

$$T_2(s) = \left[\frac{s^2-4.300s+14.170}{s^2+4.300s+14.170}\right] \quad , f_o = 1.0(10^{-3})$$

and

$$T_4(s) = -1\left[\frac{s-1.0810(10^5)}{s+1.0810(10^5)}\right] \quad , f_o = 40.8$$

$$T_4(s) = -1\left[\frac{s-2.647}{s+2.647}\right] \quad , f_o = 1.0(10^{-3})$$

The first and second order transfer functions for the minimum phase sections are:

$$T_A(s) = \frac{s^2 + 114.43}{s^2 + .7042(10^5)s + 5.0735(10^{10})}, \quad f_o = 40.8$$

$$T_B(s) = \frac{s^2 + 114.43}{s^2 + 1.726s + 30.479}, \quad f_o = 1.0(10^{-3})$$

$$T_B(s) = \frac{s^2 + 7.2943(10^{10})}{s^2 + 2.3235(10^5)s + 2.6324(10^{10})}, \quad f_o = 40.8$$

$$T_B(s) = \frac{s^2 + 43.810}{s^2 + 5.695s + 15.814}, \quad f_o = 1.0(10^{-3})$$

$$T_C(s) = \frac{10^5}{s + 3.0089(10^5)}, \quad f_o = 40.8$$

$$T_C(s) = \frac{2.451}{s + 7.375}, \quad f_o = 1.0(10^{-3})$$

By frequency scaling for the required f_o (36 kHz), second order transfer functions are obtained which meet the filter specifications as verified by the amplitude response plotted in Figure 18. The nonminimum transfer functions $T_2(s)$ and $T_4(s)$ are realized using the synthesis technique shown in Figures 12 and 13. Similarly, the transfer functions $T_A(s)$ and $T_B(s)$ are obtained using the frequency rejection network shown in Figure 14 and the transfer function $T_C(s)$ is realized using the network in Figure 15C. These sections are then cascaded as shown in Figure 19 to produce a modified raised cosine filter.

Considering the limits imposed on the operational amplifier offset voltage and gain bandwidth product and on building block component values, calculated component values for the modified raised cosine filter for the

304 Data Set are given in Figure 20. A study of Figure 20 also indicates that with a slight modification of the presently available second order building block and the use of some discrete components the filter can be realized with three building block sections. Suggested modifications in the building block to include all the configurations required for the raised cosine filters are shown in Figure 21. Because of the limits imposed by the operational amplifier slew rate, the sections are cascaded with the frequency rejection networks, which effectively serve as low pass sections, followed by the all pass sections with loss and finally the last section with an adjustable gain.

To check the amplitude and phase response of this cascaded network, a computer program, ECAP, was run on the 7094. The model of the network used and the calculated amplitude and phase response are shown in Figures 22 to 24. Also, a breadboard model was constructed using discrete components and integrated operational amplifiers.[7] The filter was built and tuned in five separate sections. The components in each section were adjusted to give the proper frequency response for the section, as shown in Figures 25 to 30. The five sections were then cascaded and the amplitude and phase response measured. The measured amplitude and phase response are plotted in Figures 31 and 32. Additional characteristics of the breadboard model are given in Figure 33. The measured and computed amplitude and phase response are well within the limits set for the 304 Data Set and the measured values of offset voltage, signal level, noise level, and power dissipation indicate that this filter should be acceptable for use in the 304 Data Set.

Conclusion

The results of this memorandum indicate that the modified raised cosine filter can be synthesized using a slightly modified version of the second order filter section developed by Department 5316. Use of the second order filter section offers the advantages of a low sensitivity network plus the economical advantages of circuit standardization.

Acknowledgments

Mr. G. S. Moschytz's supervision of my rotational assignment is appreciated. In addition, the contributions and assistance of W. H. D'Zio in turning the breadboard model of the filter are acknowledged.

M.S. Lane

HO-5316-MSL-EMB

M. S. LANE

Att.
References
Appendices A-C
Figures 1 - 33
App A - fig 1
App B - fig 2

Appendix A

Lattice Conversion Techniques

For the symmetrical lattice network in Figure 1A, the open-circuit impedance parameters are

$$\underline{Z}_L = \begin{bmatrix} .5(Z_b+Z_a) & .5(Z_b-Z_a) \\ .5(Z_b-Z_a) & .5(Z_b+Z_a) \end{bmatrix}$$

For the symmetrical T in Figure 1B, the open-circuit impedance parameters are

$$\underline{Z}_T = \begin{bmatrix} (Z_1+Z_2) & (Z_2) \\ (Z_2) & (Z_1+Z_2) \end{bmatrix}$$

For the symmetrical T in Figure 1B to be equivalent to the lattice in Figure 1A the open-circuit impedance parameters must be equal. This condition is met if

$$Z_1 = Z_a$$

$$Z_2 = .5(Z_b-Z_a)$$

The short-circuit admittance parameters for the lattice network in Figure 1C are

$$\underline{Y}_L = \begin{bmatrix} .5(Y_b+Y_{a1}+Y_{a2}) & .5(Y_b-Y_{a1}-Y_{a2}) \\ .5(Y_b-Y_{a1}-Y_{a2}) & .5(Y_b+Y_{a1}+Y_{a2}) \end{bmatrix}$$

$$\underline{Y}_L = \begin{bmatrix} .5(Y_b+Y_{a1}) + .5\ Y_{a2} & .5(Y_b-Y_{a1}) - .5\ Y_{a1} \\ .5(Y_b-Y_{a1}) - .5\ Y_{a2} & .5(Y_b+Y_{a1}) + .5\ Y_{a1} \end{bmatrix}$$

$$\underline{Y}_L = \begin{bmatrix} Y_{11}' + Y_{11}'' & Y_{12}' + Y_{12}'' \\ Y_{12}' + Y_{12}'' & Y_{11}' + Y_{11}'' \end{bmatrix}$$

Considering the primed and double-primed parameters as referring to two parallel networks the equivalent parallel connection of these networks corresponds to the bridged T network shown in Figure 1D.

Similarly, the open circuit impedance parameters for the lattice network in Figure iE are

$$\underline{Z_L} = \begin{bmatrix} .5(Z_{b1}+Z_{b2}+Z_a) & .5(Z_{b1}+Z_{b2}-Z_a) \\ .5(Z_{b1}+Z_{b2}-Z_a) & .5(Z_{b1}+Z_{b2}+Z_a) \end{bmatrix}$$

$$\underline{Z_L} = \begin{bmatrix} .5(Z_{b1}+Z_a) + .5\ Z_{b2} & .5(Z_{b1}-Z_a) + .5\ Z_{b2} \\ .5(Z_{b1}-Z_a) + .5\ Z_{b2} & .5(Z_{b1}-Z_a) + .5\ Z_{b2} \end{bmatrix}$$

$$\underline{Z_L} = \begin{bmatrix} Z_{11}' + Z_{11}'' & Z_{12}' + Z_{12}'' \\ Z_{12}' + Z_{12}'' & Z_{11}' + Z_{11}'' \end{bmatrix}$$

Considering the primed and double-primed parameters as referring to two networks in a series-series configuration, the equivalent series connection of these networks is shown in Figure 1F.

Finally the combination of all these conversions results in the two equivalent networks shown in Figures IG and IH.

Appendix B

The loaded transfer function of the constant resistance lattice in Figure 2B is

$$T(s) = \frac{Z_{21}R}{\Delta Z + Z_{11}R}$$

$$\underline{Z} = \begin{bmatrix} .5(Z_b+Z_a) & .5(Z_b-Z_a) \\ .5(Z_b-Z_a) & .5(Z_b+Z_a) \end{bmatrix}$$

$$\Delta Z = Z_a Z_b = R^2$$

$$T(s) = \frac{.5(Z_b-Z_a)R}{R^2 + .5(Z_b+Z_a)R}$$

$$T(s) = \frac{.5\left(\frac{R^2}{Z_a} - Z_a\right)}{R + .5\left(\frac{R^2}{Z_a} + Z_a\right)} = \frac{R^2 = Z_a{}^2}{R^2 + 2RZ_a + Z_a{}^2}$$

$$T(s) = \left(\frac{R - Z_a}{R + Z_a}\right)$$

References

1. Moschytz, G. S., "Active RC Filter Building Blocks Using Frequency Emphasizing Networks Part 1," MM67-5316-1, January 3, 1967.
2. Reinecke, H. D., "IMB 7094 Computer Program for Polynomial in N from Network Schematic," Memorandum for File, April 2, 1965.
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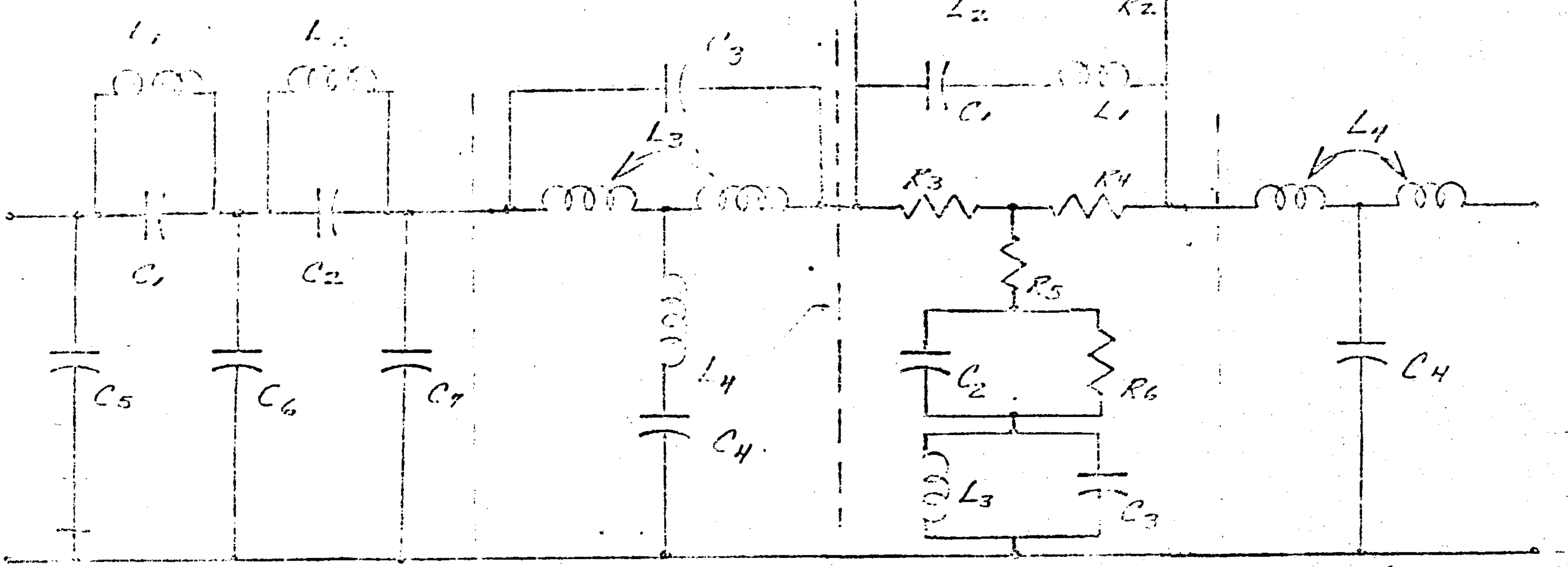
4. Moraller, J. A., "SUPROX, A General Purpose Successive Approximation Computer Program," MM67-2112-15, March 27, 1967.
5. Moschytz, G. S., "Linear Active R.C. Networks," MM66-5316-8, August 17, 1967.
6. Lee, S. C., "Sensitivity Minimization in Active RC Integrated Circuit Design," MM66-2623-9.
7. Kolibaba, M. C., Medill, D. G., and D'Zio, W. H., "Active Building Blocks Using Frequency Emphasizing Networks," Memorandum for File, Case File 38763, September 11, 1967.
8. O'Neill, J. F., Technical Report 400-159 Active RC Delay Networks Using Operational Amplifiers," New York University School of Engineering and Science, Department of Electrical Engineering, May 1967.

100% Roll Off Raised Cosine Filter
40.8 KB Data



$R_0 = 600\Omega$ $f_{30db} = 40.8$ KHz $b = 1.75$ $f_\infty = 24.5$ KHz | $f_p = 27.3$ KHz $f_0 = 37.5$ KHz $f_{\pi/2} = 17.1$ KHz

L_1 = 4.095 mh.	C_1 = 1282. pf	L_1 = 2.95 mh.	R_1 = 510. Ω
L_2 = 2.9[illegible] mh.	C_2 = 4695. pf	L_2 = 2.60 mh	R_2 = 116.4 Ω
L_3 = [illegible].92 mh.	C_3 = 4750. pf	L_3 = 2.194 mh	R_3 = 600. Ω
L_4 = 1.[illegible] mh.	C_4 = 24,80[illegible]. pf	L_4 = 11.15 mh	R_4 = 600. Ω
	C_5 = 3728. pf	C_1 = 6105. pf	R_5 = 706. Ω
	C_6 = 1[illegible]37[illegible]. pf	C_2 = 7[illegible]10. pf	R_6 = 3090. Ω
	C_7 = 1305. pf	C_3 = 8190. pf	
		C_4 = 30,950. pf	

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ISSUE	ENGR / DRAWN	TITLE	
9/15/67	M.S.L.	Figure 1 — 100% Roll off Raised Cosine Filter	BELL TELEPHONE LABORATORIES INCORPORATED — SHEET 16 — NO. OF SHEETS PER SET

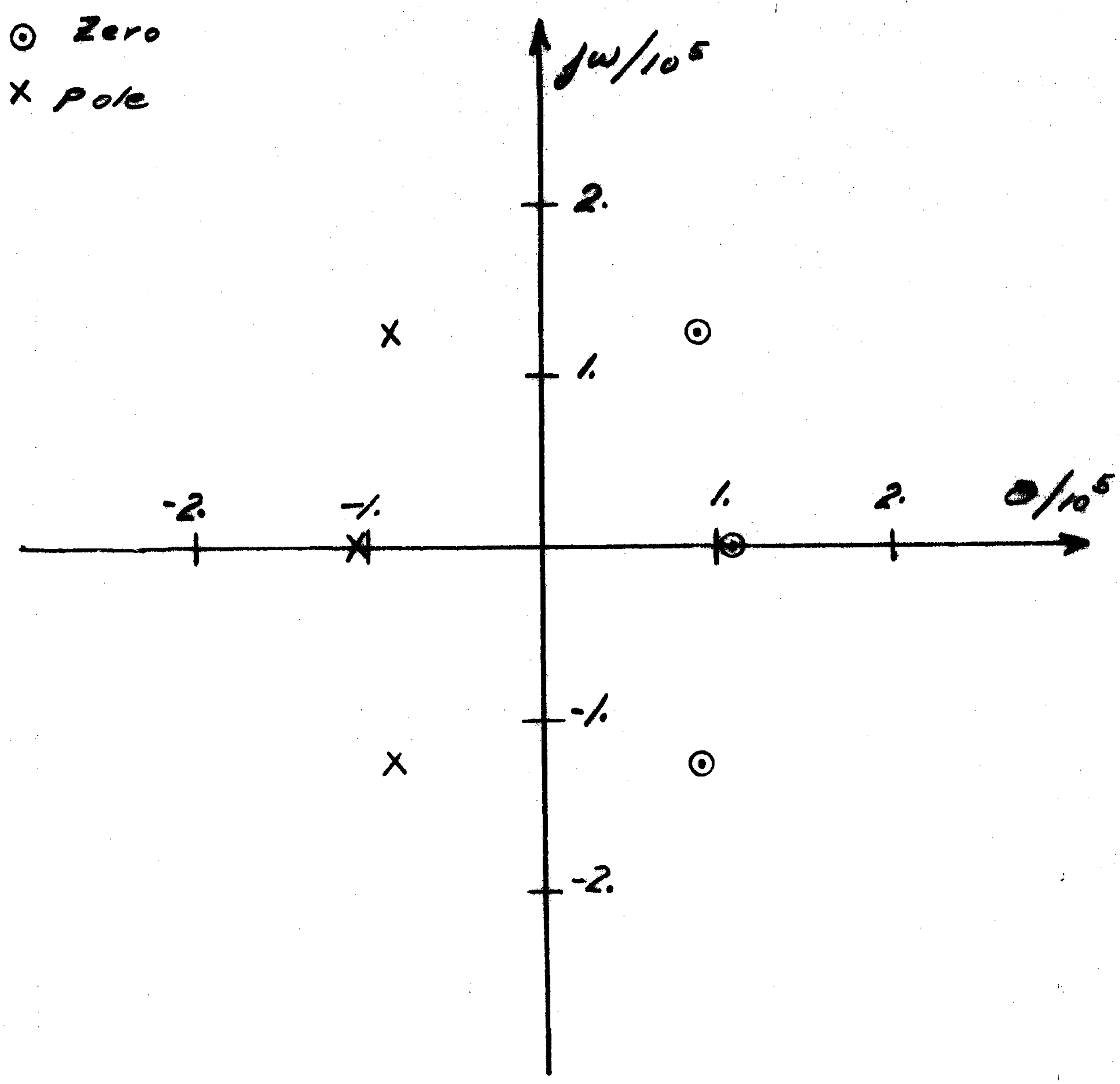
Specifications for Modified Raised Cosine Filter 304 Data Set

Amplitude Response (36 KB Data)	0-36 KHz	$\frac{\pi f}{72(10^3)} \cot \frac{\pi f}{72(10^3)} \pm .03$
	36-61 KHz	< -30 db.
	61-97 KHz	< -40 db.
	f > 97 KHz	< -50 db.
Phase Response	0-36 KHz	Linear
Input Impedance	600 Ω	
Output Impedance	600 Ω	
Temperature Range	40°F - 140°F	

ISSUE	ENGR / DRAWN	TITLE	
9/14/67	M.S.L.	FIGURE 2 Specifications	BELL TELEPHONE LABORATORIES INCORPORATED; NO. OF SHEETS PER SET; SHEET 17

7 16

NONMINIMUM PHASE SECTIONS
MODIFIED RAISED COSINE FILTER
40.8 KB Data



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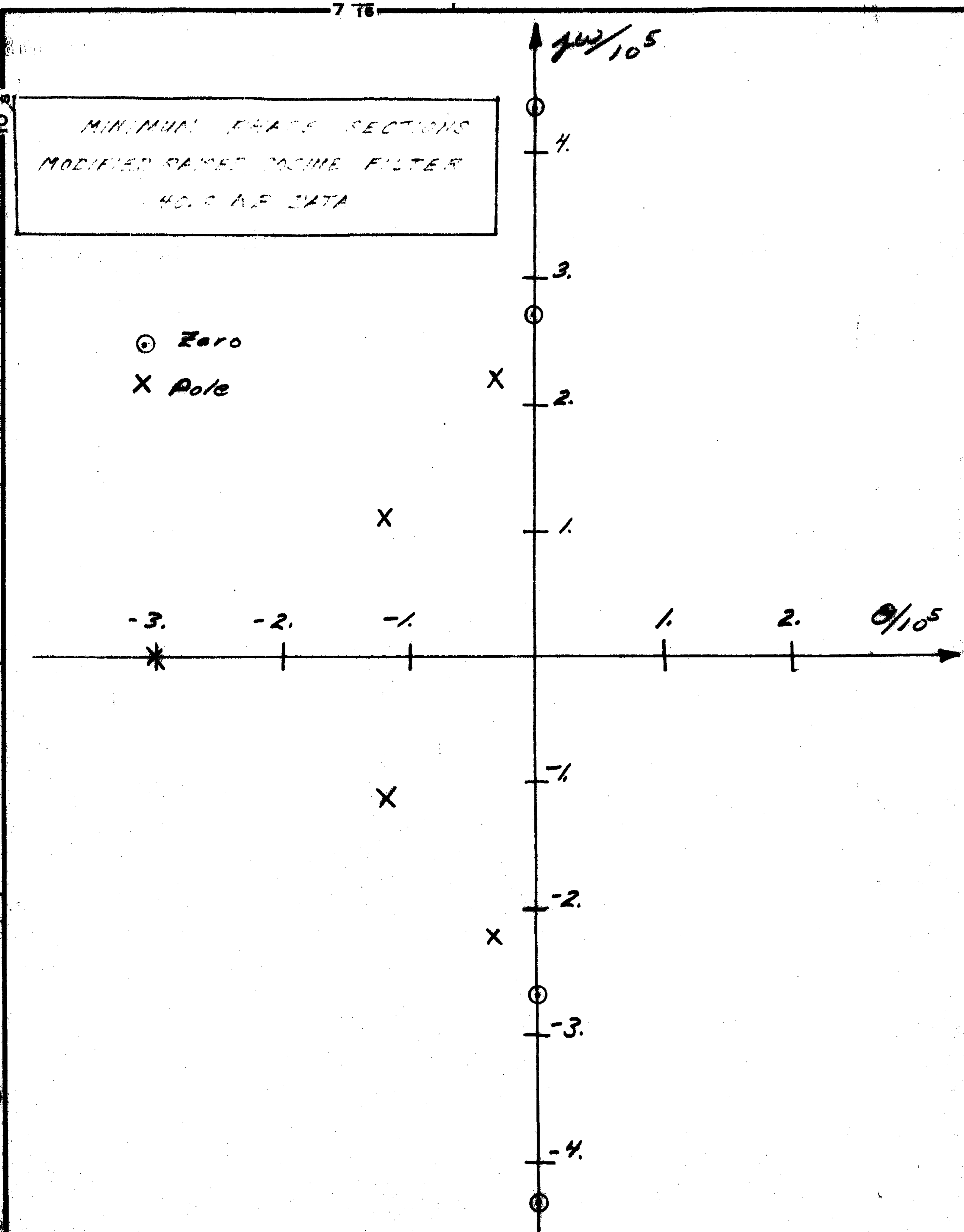
9/14/67	H.S.L.	FIGURE 3		18



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TITLE: FIGURE 4

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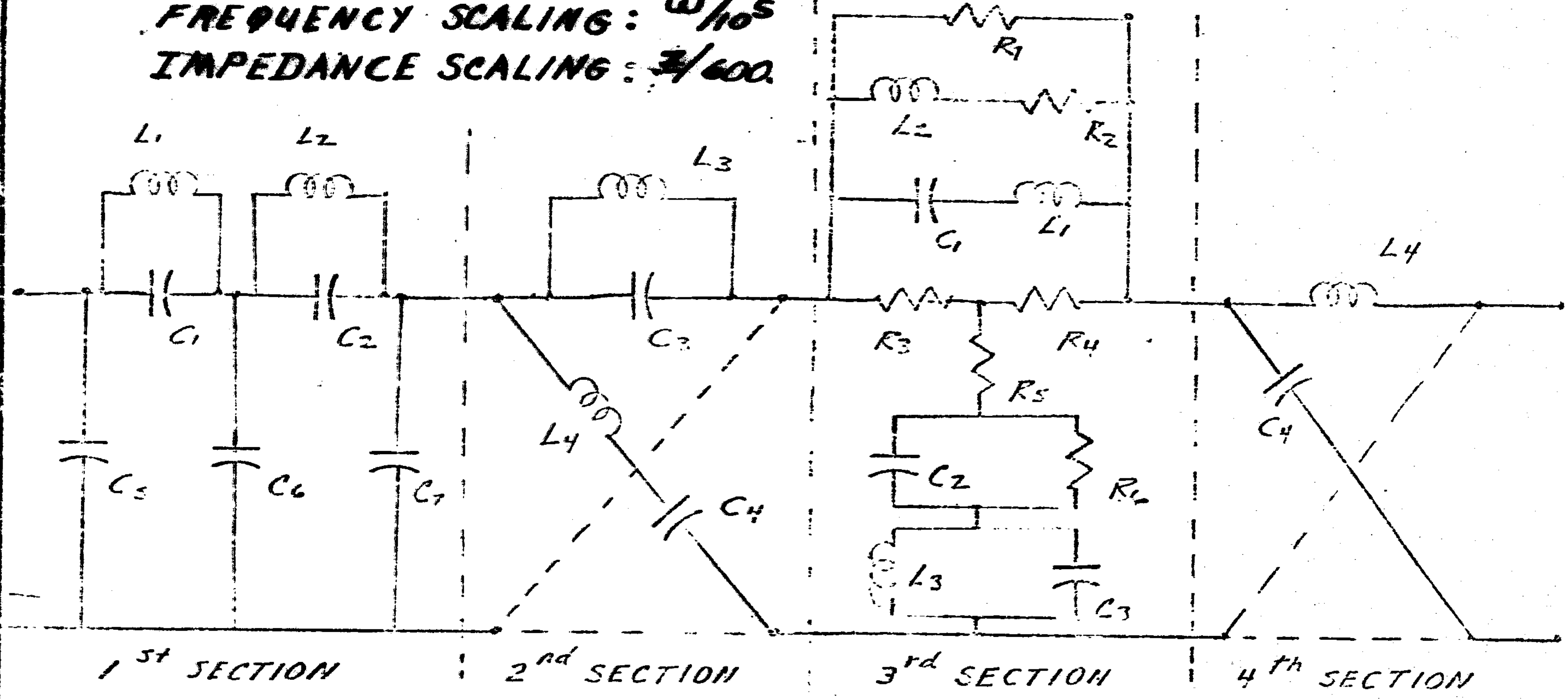
FREQUENCY SCALING: $\omega/10^5$
IMPEDANCE SCALING: 3/600



10 5/8

L_1 = .6825 h	C_1 = .0769 f	L_1 = .4917 h	C_3 = .4914 f	R_5 = 1.176 Ω
L_2 = .4266 h	C_2 = .2817 f	L_2 = .4333 h	C_4 = .9285 f	R_6 = 5.150 Ω
L_3 = .7433 h	C_3 = .5700 f	L_3 = .3656 h	R_1 = .8500 Ω	
L_4 = .5686 h	C_4 = .7400 f	L_4 = .9250 h	R_2 = .1940 Ω	
C_7 = .0783 f	C_5 = .2237 f	C_1 = .3663 f	R_3 = 1.0 Ω	
	C_6 = .8622 f	C_2 = .4344 f	R_4 = 1.0 Ω	

NORMALIZED 100% ROLL OFF RAISED COSINE FILTER
40.8 KB Data

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TITLE Figure 5 NORMALIZED RAISED COSINE FILTER

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NONMINIMUM PHASE SECTIONS
MODIFIED RAISED COSINE FILTER
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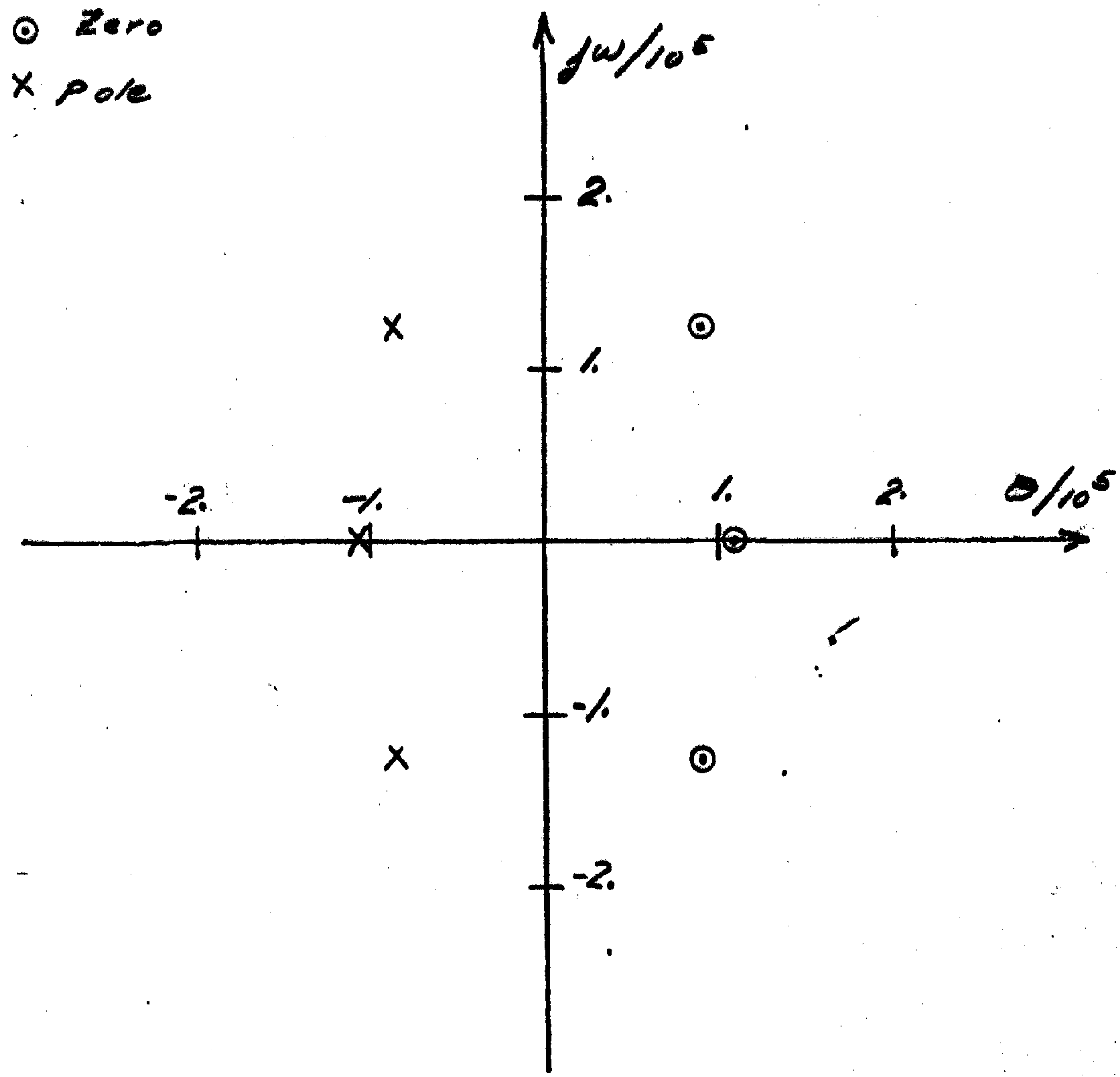

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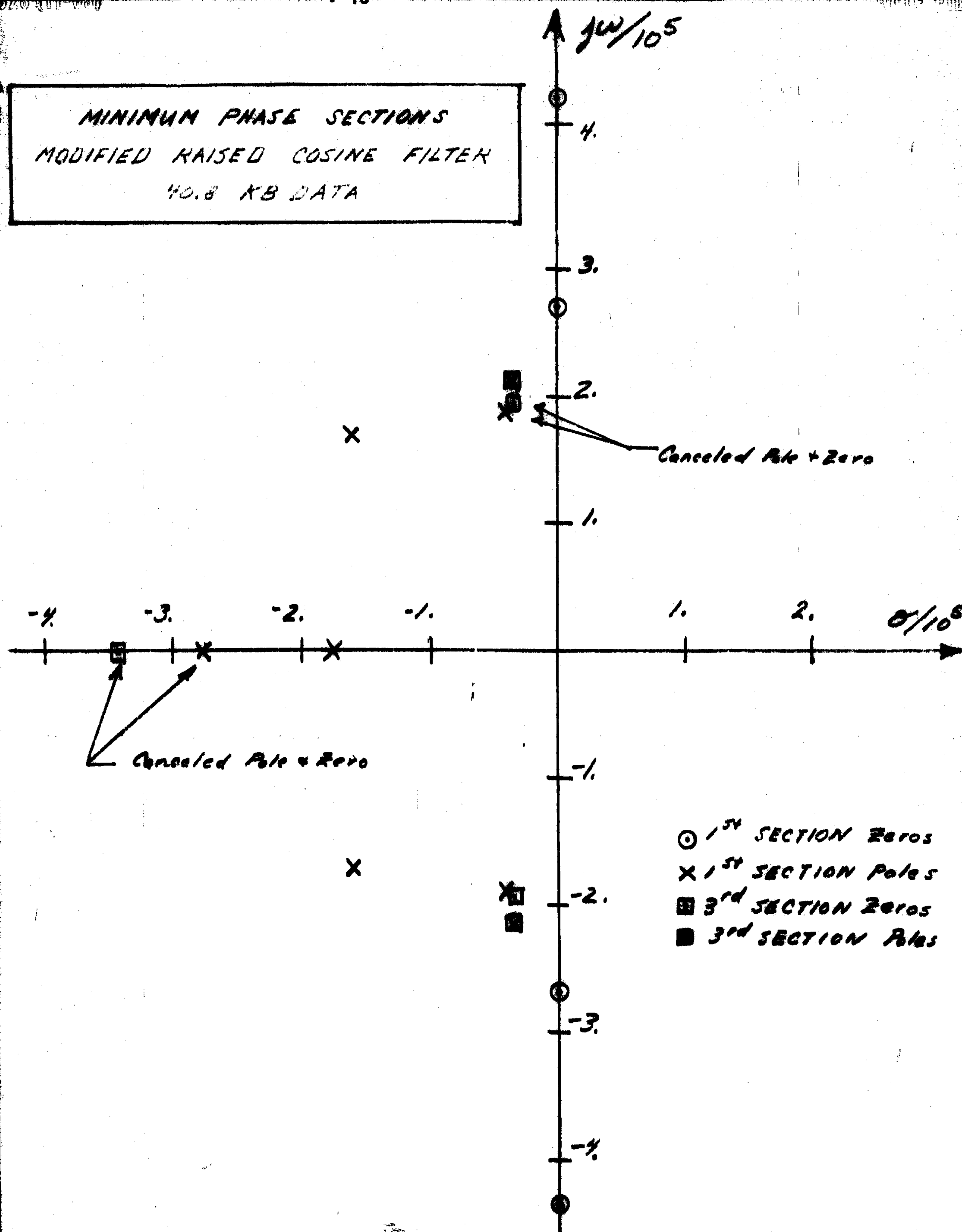


DATE	BY	TITLE	SHEET
9/14/67	M.S.L.	FIGURE 7	22

Active Filter Building Block

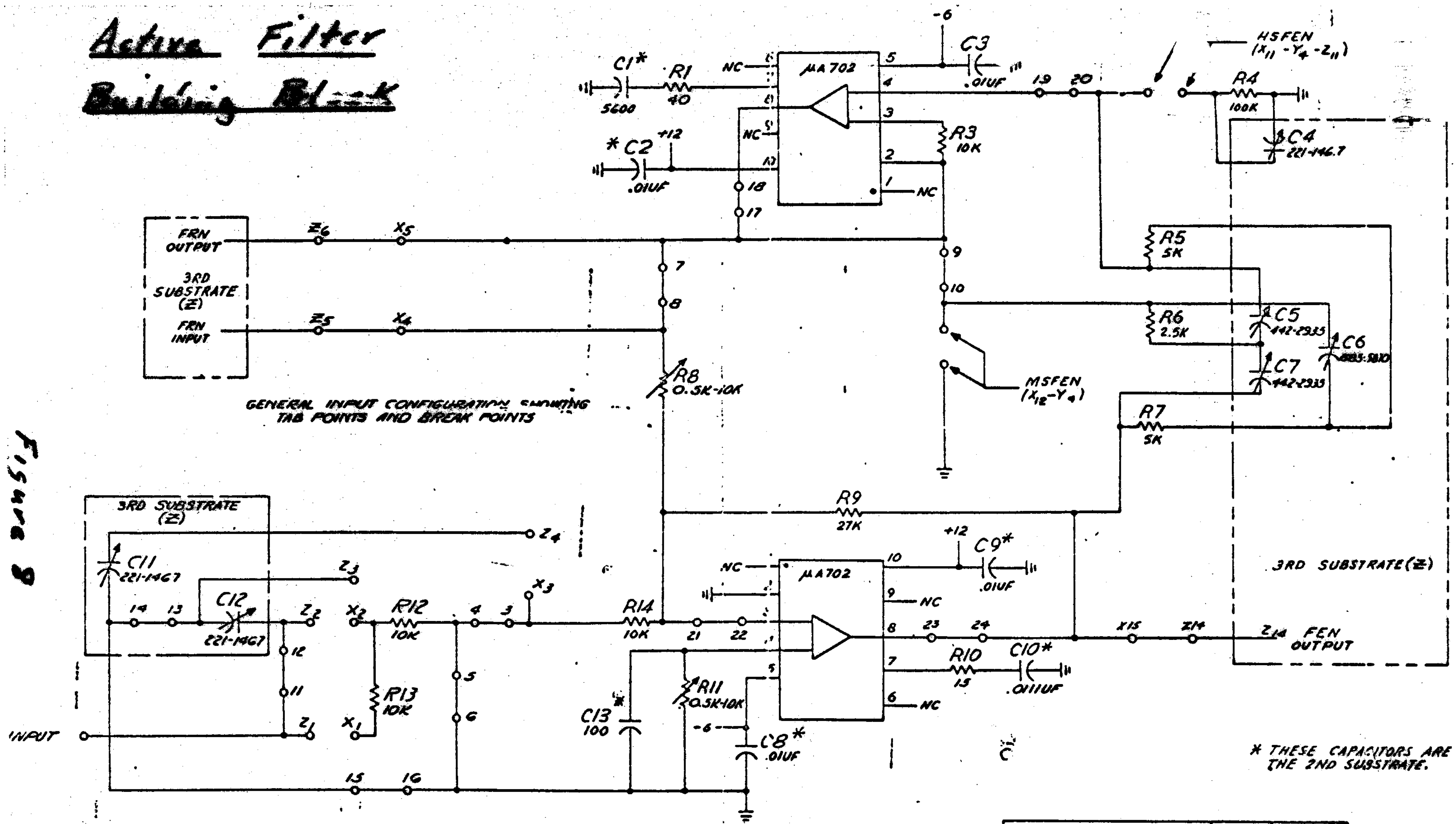


Figure 8

NOTES:

1. UNLESS OTHERWISE SPECIFIED:
   RESISTANCE VALUES ARE IN OHMS.
   CAPACITANCE VALUES ARE IN PICOFARADS
   VALUES PRECEDED BY THE SYMBOL + (PLUS)
   OR - (MINUS) ARE IN VOLTS.
2. ⏚ GROUND RETURN
3. USE FOLLOWING COMBINATIONS FOR INPUT FILTERS

FILTER	BREAK POINTS	TAB CONN
HPF	3-4, 15-16	Z_4-X_3, Z_3-X_2.
LPF	11-12, 5-6	Z_4-X_3, Z_1-X_1, Z_2-X_2
BPF	13-14, 5-6	Z_4-X_3, Z_3-X_2
RES.	11-12, 5-6, 15-16	Z_1-X_1, Z_4-X_3, Z_3-X_2, GND Z_2
FOR FRN BREAK 3-4		Z_5-X_4

4. ALL CAPACITORS ±10%
   R1, R4-R10 = 1%, UNSHUNTED PORTION OF R8+R11 = ±5%
   R3, R11-R14 = 5%
   R2 NOT TRIMMED
5. BREAK NUMBERS 17-18 AND 19-20 EXIST DUE TO THE ABSENCE OF OPERATIONAL AMPLIFIER AND PRESENCE OF BEAM LEADED TRANSISTORS.
6. HS - HIGH SELECTIVITY
   MS - MEDIUM SELECTIVITY

	FEN	FRN
INPUT/OUTPUT OPEN BETWEEN TERMINALS	Z_1-Z_{14}	Z_5 / Z_6 7 - 8
HS OPERATION OPEN BETWEEN TERMINALS CONNECT BETWEEN TABS	1-2 $Z_{11}-Y_4$ X_{10}	[illegible] $Z_{11}-Y_4$ - X_{10}
MS OPERATION OPEN BETWEEN TERMINALS CONNECT BETWEEN TABS	1-2 9-10 Y_4-X_{12}	

Figure 8

Building Block Parameters

	Min.	Typical	Max.
Frequency Range	7.2 KHz		72 KHz
Signal Level (Sinusoidal)		.6 Vp-p	1.0 Vp-p
Input off set voltage		2-5 mv	
Positive Supply Voltage		+12.0 v	
Negative Supply Voltage		-6.0 v	
Temperature Range	10°C		70°C
Power Dissipation		270 mw	

Component Values

Resistors	Routine	Available
Range	See Figure 8	
Max R/Substrate	0.5 mΩ	5 mΩ
Initial Precision	0.1%	0.02%
Aging (20 years)	1%	.05%
Temp Coef $\frac{dR/R}{°C}$	-50 to -100±15 $\frac{ppm}{°C}$	0 to -1000 $\frac{ppm}{°C}$
Tunability	+20% ± 1%	+50% ± .1%
Tracking	±5 ppm/°C	

Capacitors	$Au/NiCr/Ta_2O_5/Ta$
Range	See Figure 8
Max C/Substrate	.05 µf
Initial Precision	1-5 %
Stability (Humidity & aging)	0.2%
Temp. Coeff. $\frac{dc/c}{°C}$ (25°C-65°C)	+235 ± 20 $\frac{ppm}{°C}$
Tracking	± 15 ppm/°C
Dielectric Loss	.003 to .006
Guaranteed Matching of RC Temp Coeff.	± 25 ppm/°C

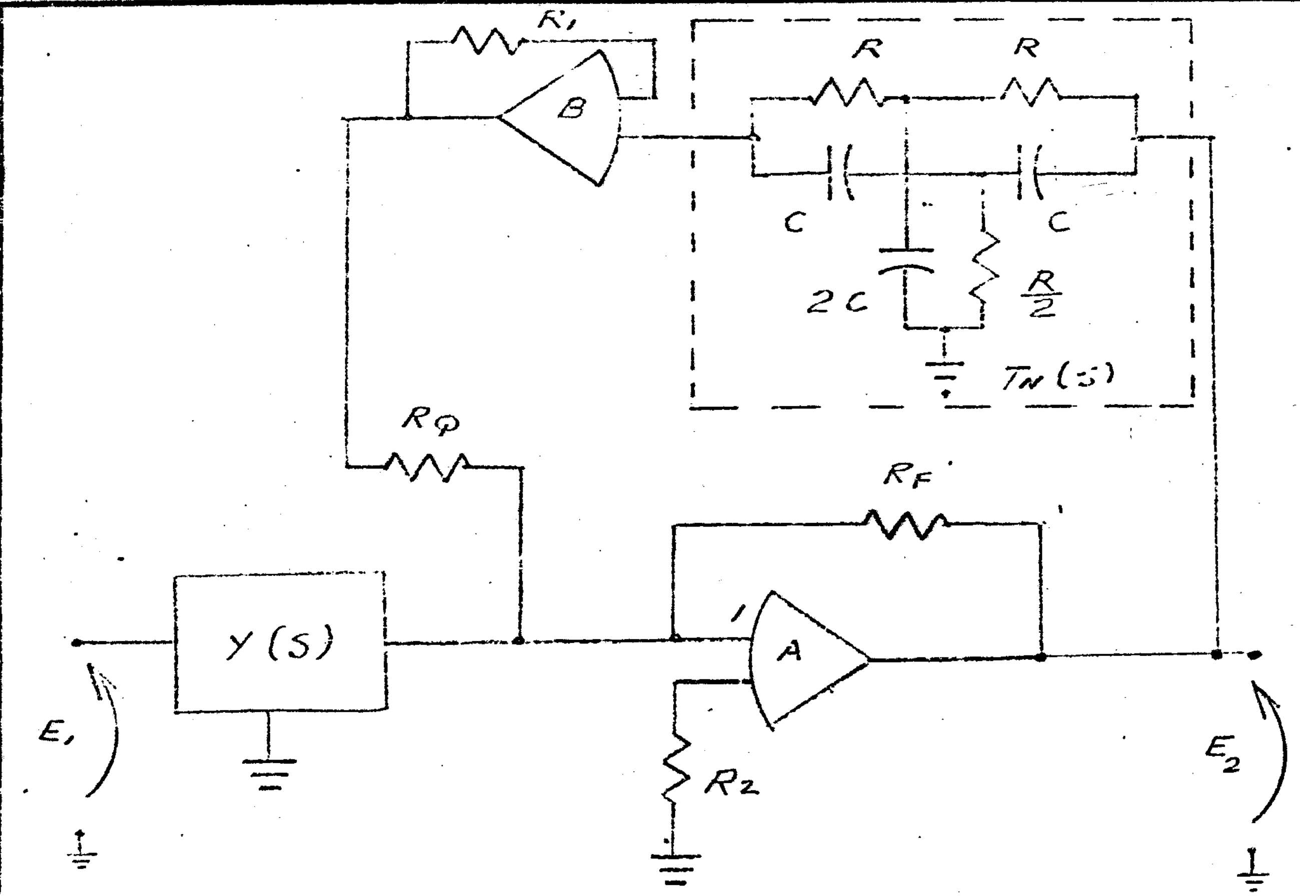
ISSUE 9/14/67

ENGR W.S.L.

DRAWN

TITLE

FIGURE 10
FREQUENCY EMPHASIZING NETWORK



* Does not include Amp. biasing circuits

$$\frac{E_2}{E_1} = \frac{-R_F}{1+\frac{R_F}{R_\varphi}} \left[Y(s) \right] \left[\frac{S^2 + \frac{\omega_1}{q_1} S + \omega_1^2}{S^2 + \frac{\omega_1}{q_1\left(1+\frac{R_F}{R_\varphi}\right)} S + \omega_1^2} \right]$$

$$T_N(s) = \frac{S^2 + \omega_1^2}{S^2 + \frac{\omega_1}{q_1} S + \omega_1^2}$$

$$\omega_1 = \frac{1}{RC}$$

$$q_1 = .25$$

$$R_1 = 2R$$

R_z = Resistance to Grd on Terminal 1 of A op. Amp.

Low Pass Filter:

$$Y(s) = \frac{K_r}{s^2 + \frac{\omega_1}{q_1} s + \omega_1^2}$$

High Pass Filter:

$$Y(s) = \frac{K_r \cdot S^2}{S^2 + \frac{\omega_1}{q_1} S + \omega_1^2}$$

Band Pass Filter:

$$Y(s) = \frac{K_r \cdot S}{S^2 + \frac{\omega_1}{q_1} s + \omega_1^2}$$

Resonator

$$Y(s) = \frac{K_r(S + \omega_z)}{S^2 + \frac{\omega_1}{q_1} s + \omega_1^2}$$

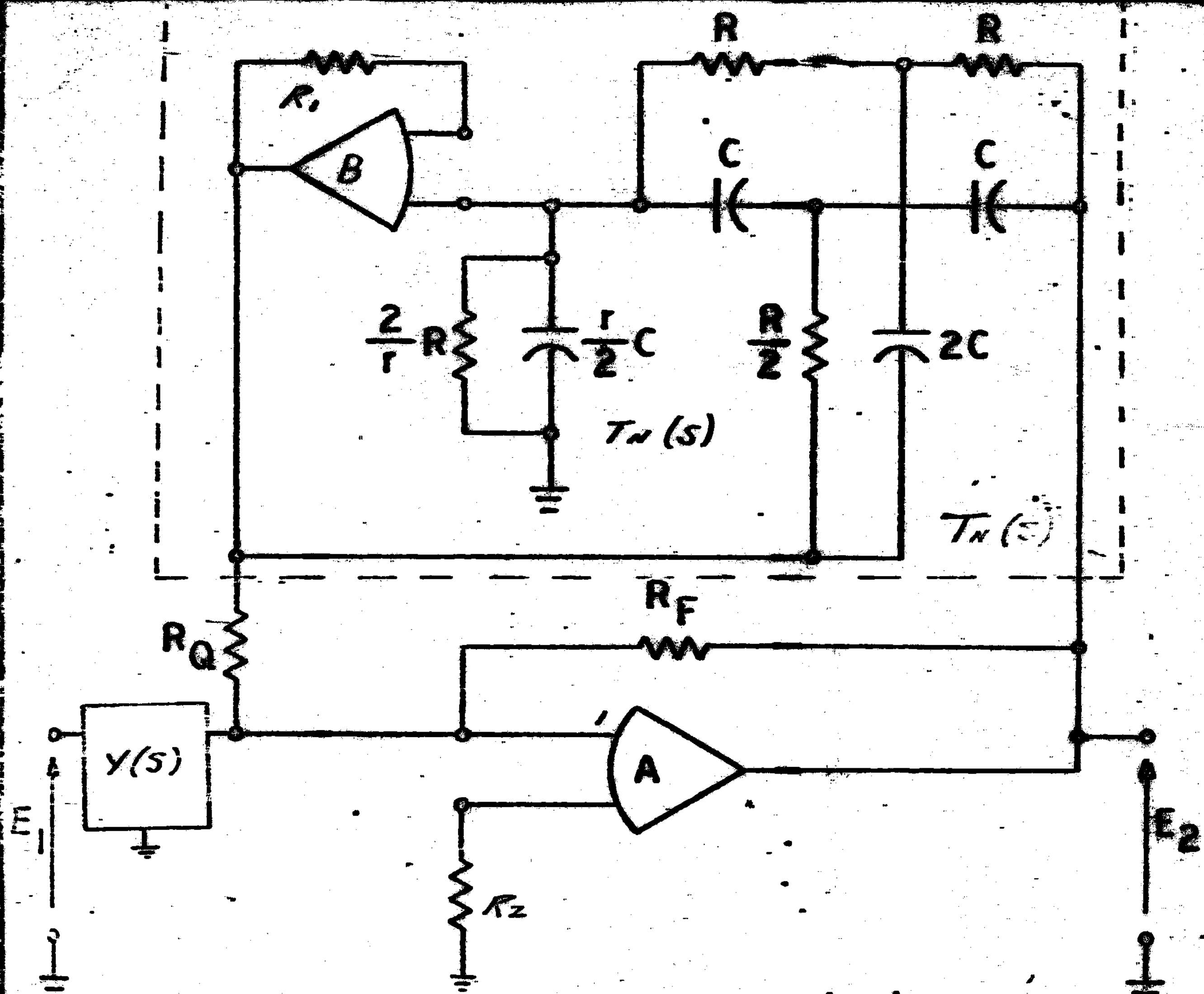
Conjugate-Complex Poles + Zeros:

$$Y(s) = \frac{K_r(s^2 + \frac{\omega_2}{q_2} S + \omega_2^2)}{(s^2 + \frac{\omega_1}{q_1} s + \omega_1^2)}$$

BELL TELEPHONE LABORATORIES INCORPORATED

NO. OF SHEETS PER SET

SHEET 25



Does not include Amp. biasing circuit

$$\frac{E_2}{E_1} = -Y(s)\left[\frac{R_F}{\left(1+\frac{[illegible]}{R_Z}\right)}\right]\left[\frac{S^2+[illegible]\,S+\omega_N^2}{S^2+\frac{[illegible]}{[illegible]\left(1+[illegible]\right)}S+\omega_N^2}\right]$$

$$T_N(s) = \frac{K_{NN}\,(s^2+\omega_N^2)}{s^2+\frac{\omega_N}{Q_{NN}}s+\omega_N^2}$$

$K_{NN} = \frac{1}{[illegible]}$

$\omega_N = \frac{1}{RC}$

$Q_{NN} = \frac{1}{2}\left(\frac{[illegible]}{r}\right)$

$R_1 = 2R \parallel \frac{2}{r}R$

R_Z = Resistance to Gnd on Terminal 1 of A op Amp

Low Pass Filter:

$Y(s) = \frac{K_1}{s^2+\frac{[illegible]}{[illegible]}s+\omega_N^2}$

High Pass Filter:

$Y(s) = \frac{K_1 \cdot s^2}{s^2+[illegible]\,s+\omega_N^2}$

Band Pass Filter:

$Y(s) = \frac{K_1\, s}{s^2+[illegible]\,s+\omega_N^2}$

[illegible]:

$Y(s) = \frac{K_1 \cdot [illegible]}{s^2+[illegible]\,s+\omega_N^2}$

[illegible]:

$Y(s) = K_1 \frac{(s^2+[illegible]\,s+\omega_N^2)}{(s^2+[illegible]\,s+\omega_N^2)}$

4/14/64

FIGURE 11

[illegible]

BELL TELEPHONE LABORATORIES

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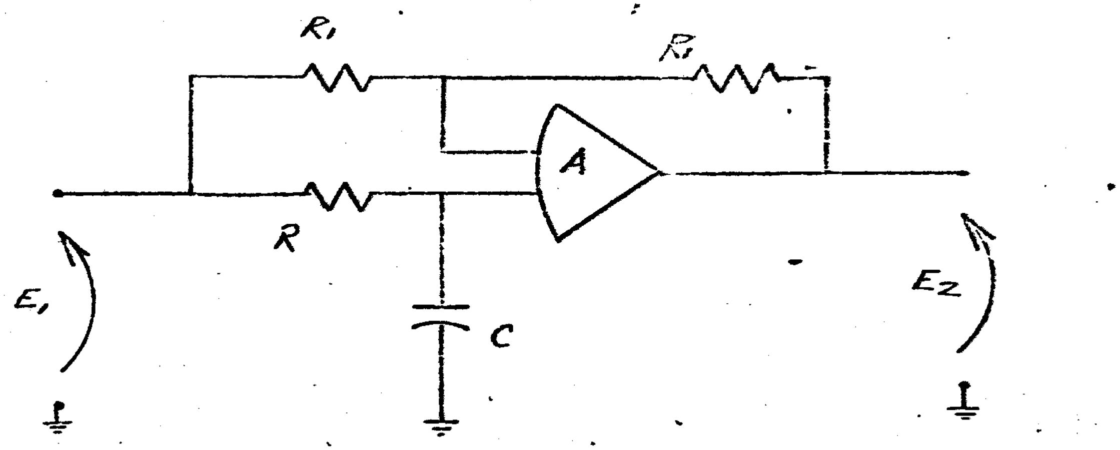
E-1812-A-1 (9-65)

$\omega_0 = \frac{1}{RC}$

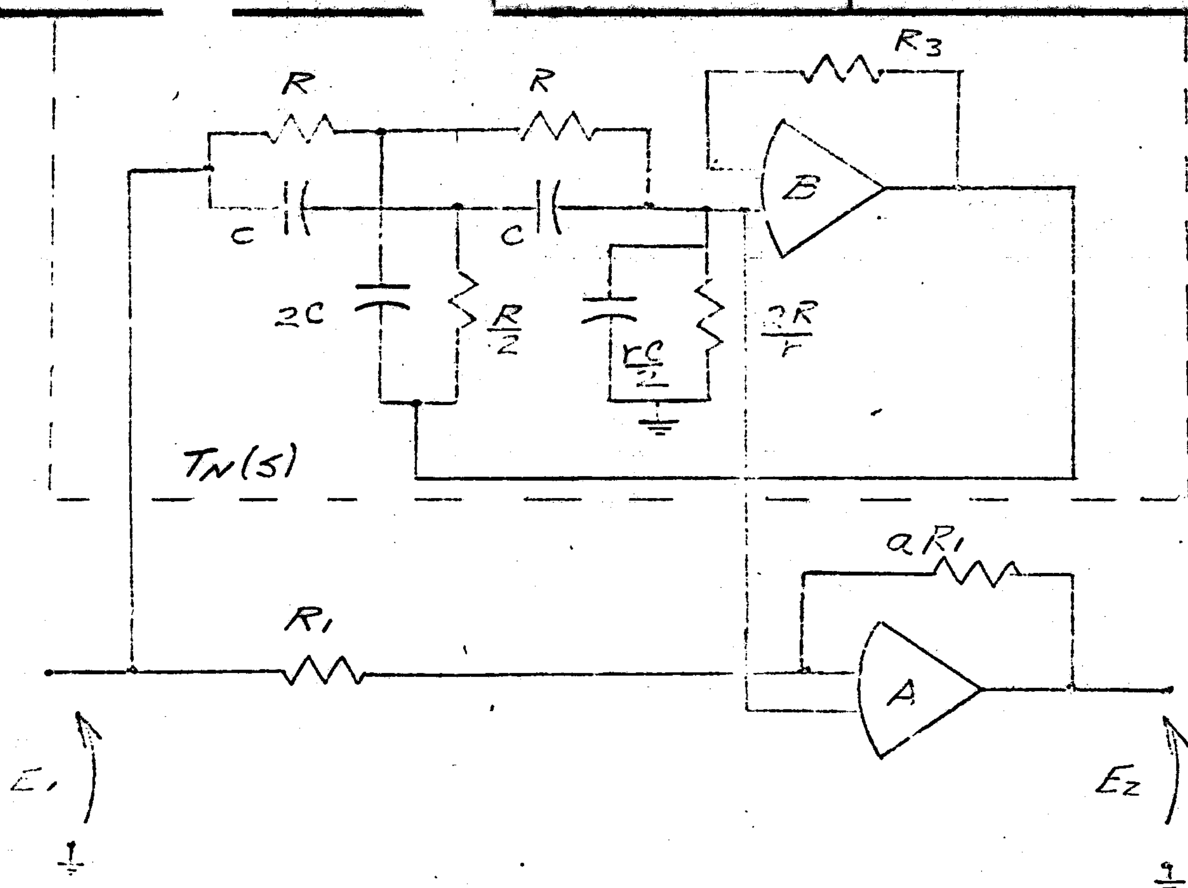
$R_1 = 2R$



* Does not include Amp. biasing circuits

$$\frac{E_2}{E_1} = \frac{-1[S - \omega_0]}{[S + \omega_0]}$$

ISSUE	ENGR	TITLE	BELL TELEPHONE LABORATORIES INCORPORATED
9/14/67	M. S. L.	FIGURE 12	
	DRAWN	1st Order All Pass Network	NO. OF SHEETS PER SET — SHEET 27



$$T_N(S) = \frac{K_{Na}\left(S^2 + \omega_N^2\right)}{\left(S^2 + \frac{\omega_N}{q_{Na}} S + \omega_N^2\right)}$$

$$K_{Na} = \frac{1}{1+r}$$

$$\omega_N = \frac{1}{RC}$$

$$q_{Na} = \frac{1+r}{2r}$$

$$R_3 = 2R \parallel \frac{2R}{r}$$

$$aR_1 \parallel R_1 = 2R \parallel \frac{2R}{r}$$

* Does not include Amp. biasing circuit

$$\frac{E_2}{E_1} = -a\left[1 - \left(1 + \frac{1}{a}\right) T_N(S)\right]$$

$$\frac{E_2}{E_1} = -a\left[\frac{S^2\left[K_{Na}\left(1+\frac{1}{a}\right) - 1\right] - \frac{\omega_N}{q_{Na}} S + \omega_N^2\left[K_{Na}\left(1+\frac{1}{a}\right) - 1\right]}{\left(S^2 + \frac{\omega_N}{q_{Na}} S + \omega_N^2\right)}\right]$$

ISSUE	ENGR / DRAWN	TITLE	
9/14/67	M. S. L.	FIGURE 13 2nd Order All Pass Network	BELL TELEPHONE LABORATORIES INCORPORATED NO. OF SHEETS PER SET SHEET 28

$$\omega_{N1} = \frac{1}{RC}$$

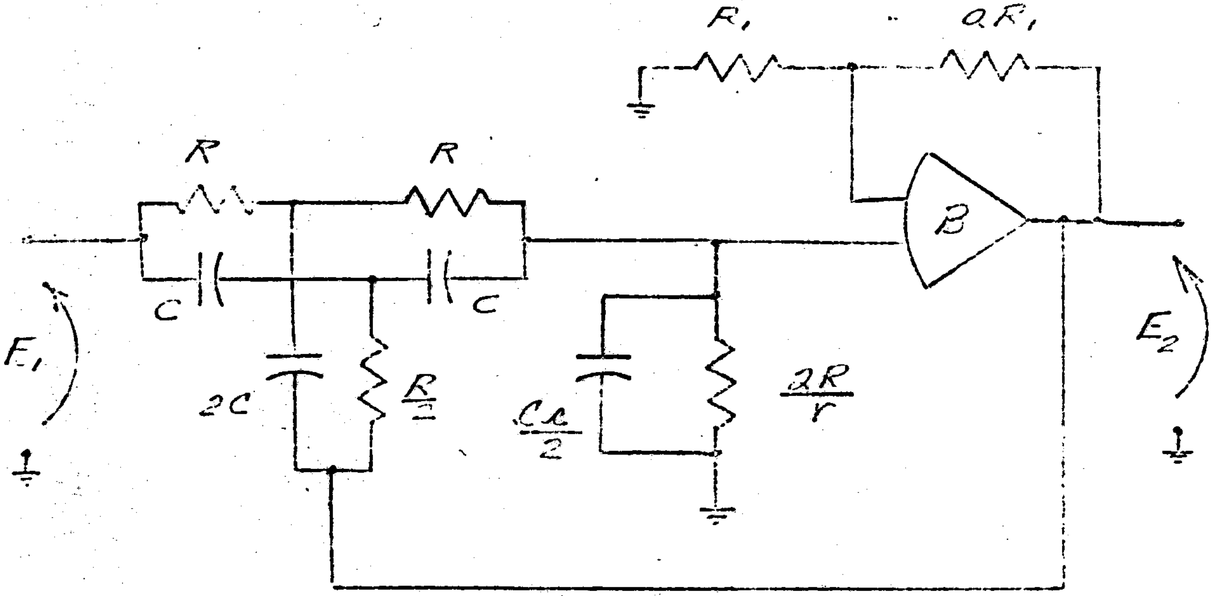
$$\omega_{N2} = \omega_{N1}\sqrt{\frac{1+r}{1+c}}$$

$$K_m = \frac{\beta}{1+c}$$

$$q_{N2} = \frac{.25\left[(1+r)(1+c)\right]^{\frac{1}{2}}}{1-\beta+(1+c)(.25)}$$

$$\beta = 1+a$$

$$\frac{aR_1}{a+1} = 2R \,//\, \frac{2R}{r}$$



* Does not includ… Amp. biasing Circuit

$$\frac{E_2}{E_1} = \frac{K_m\left(s^2+\omega_{N1}^2\right)}{\left(s^2+\frac{\omega_{N2}}{q_{N2}}s+\omega_{N2}^2\right)}$$

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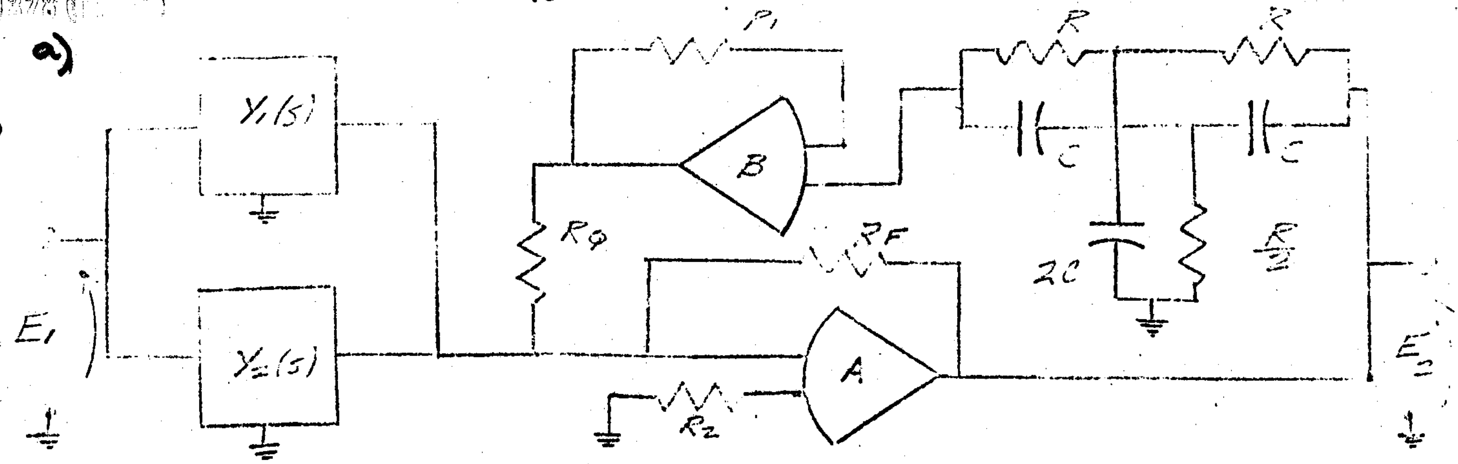
E-1813-A-1 (5-60)

ISSUE	ENGR / DRAWN	TITLE	BELL TELEPHONE LABORATORIES INCORPORATED	SHEET
9/14/67	M.S.L.	FIGURE 14 Frequency Rejection Network	NO. OF SHEETS PER SET	29

10 5/8

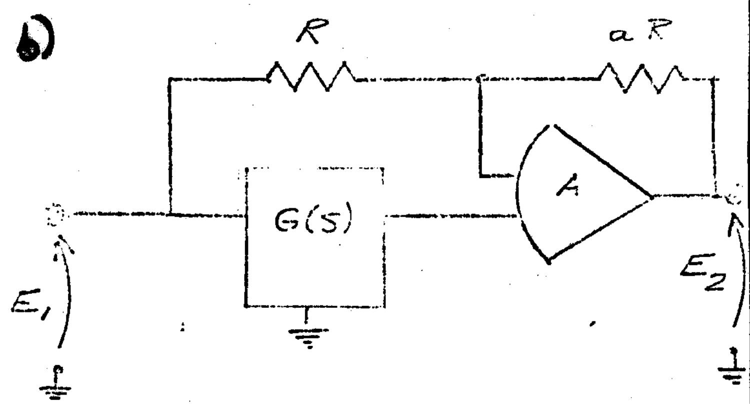
7 7/16

a)



$$\frac{E_2}{E_1} = [Y_1(s) + Y_2(s)]\left[\frac{-R_F}{1+\frac{R_F}{R_Q}}\right]\left[\frac{s^2 + \frac{\omega_1}{Q_1}s + \omega_1^2}{s^2 + \frac{\omega_1}{Q_1(1+\cdots)}s + \omega_1^2}\right]$$

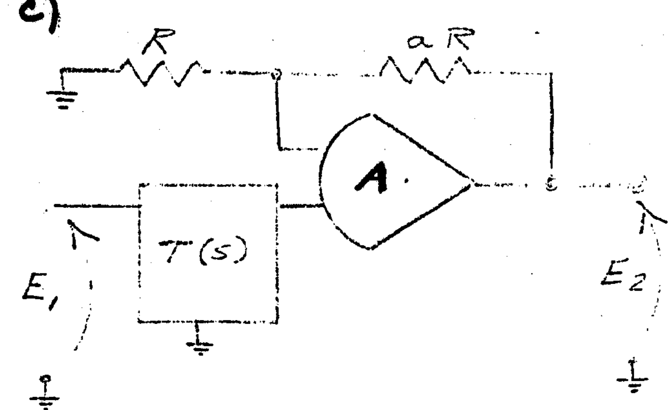
b)



$$\frac{E_2}{E_1} = -a\left[1 - \left(1 + \frac{1}{a}\right)G(s)\right]$$

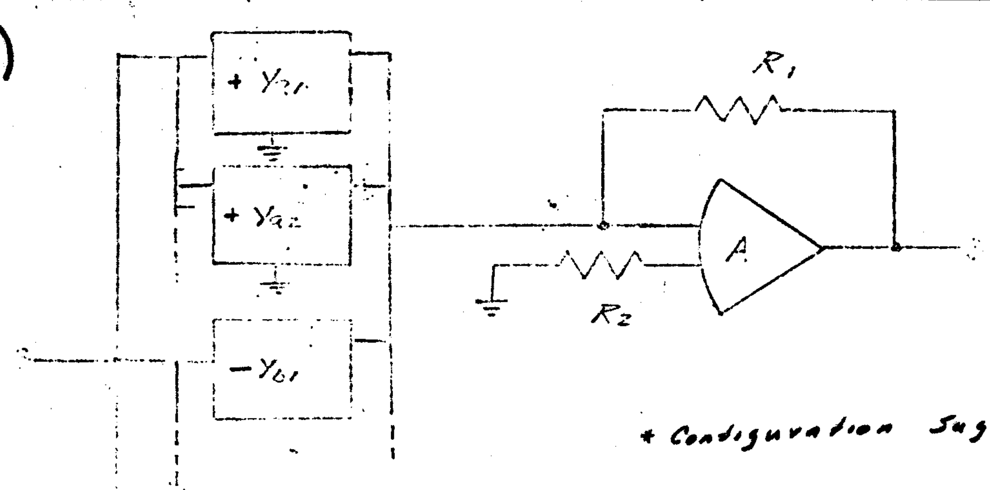
*Configuration Suggested by W. Thelen

c)



$$\frac{E_2}{E_1} = +a\,T(s)$$

d)



*Configuration Suggested by O'Neill

$$\frac{E_2}{E_1} = -R\left[\sum_{k=1}^{N} Y_{ak} - \sum_{k=1}^{M} Y_{bk}\right]$$

ISSUE	ENGR	TITLE	BELL TELEPHONE LABORATORIES INCORPORATED
9/14/67	M. Sili	FIGURE 15	
	DRAWN	Additional Synthesis Techniques	SHEET 30
			NO. OF SHEETS PER SET

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NONMINIMUM PHASE SECTIONS
MODIFIED
RAISED COSINE FILTER
40.8 KB DATA

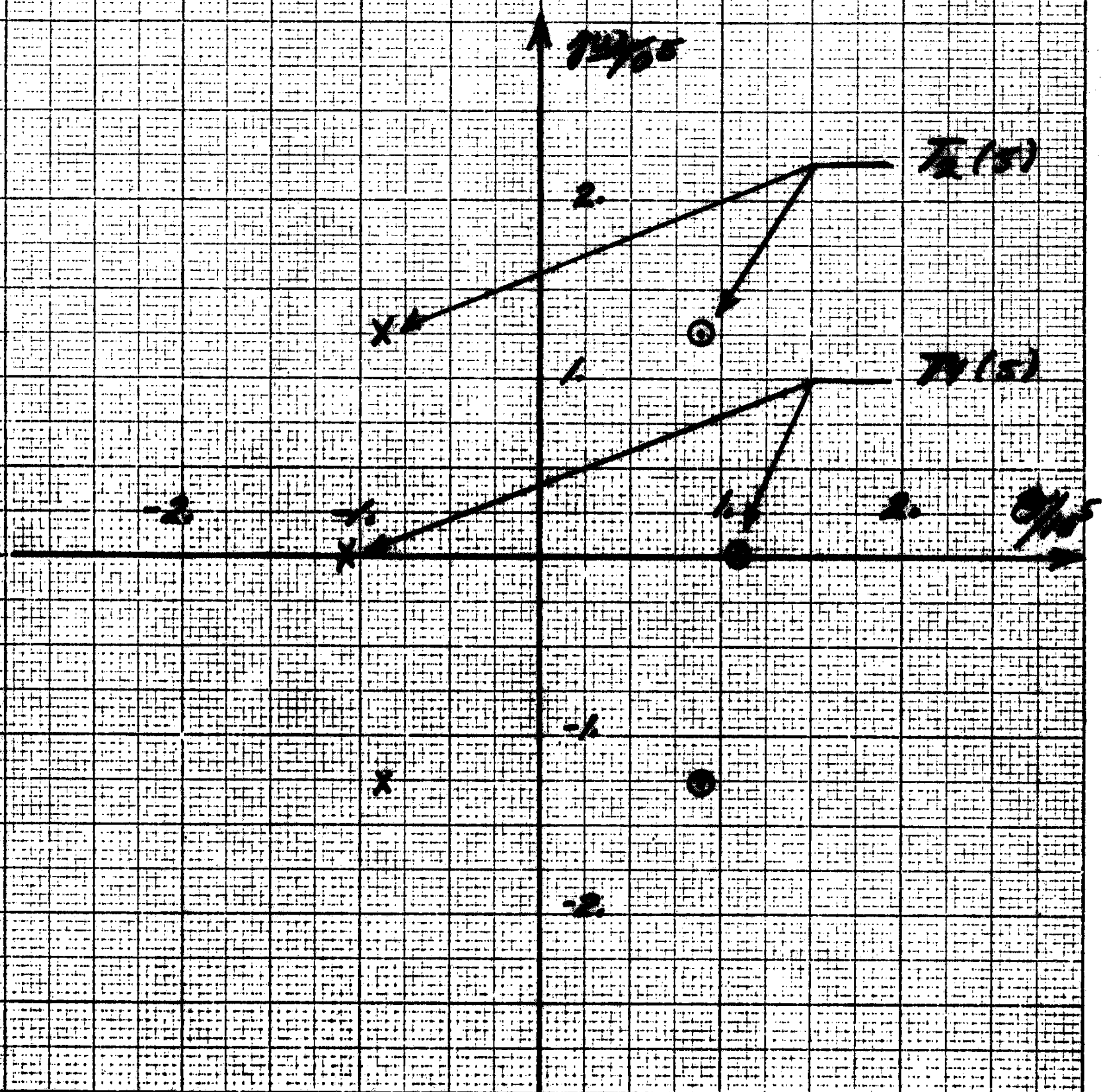


FIGURE 16

HSL
9/14/61

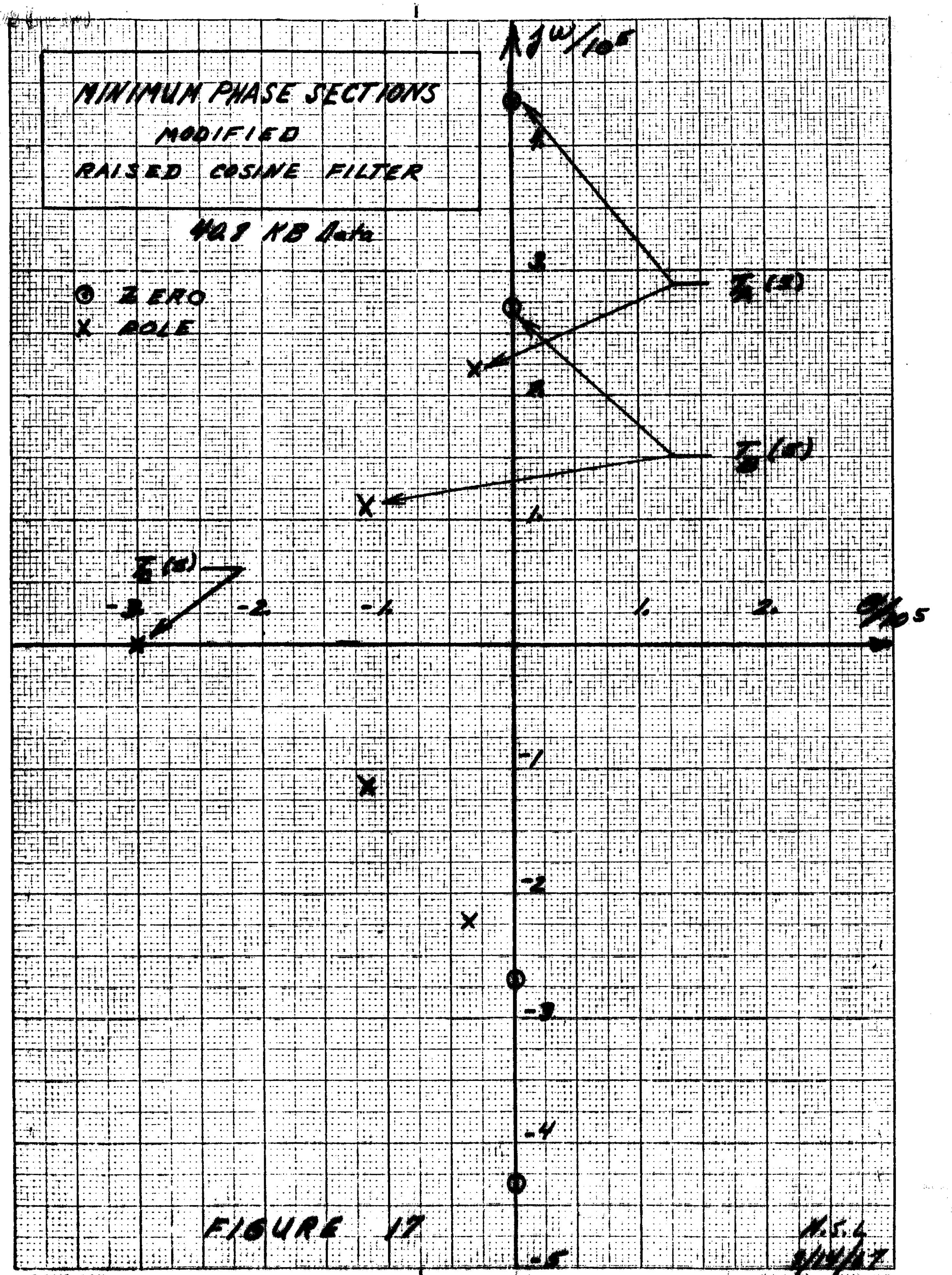

MINIMUM PHASE SECTIONS
MODIFIED
RAISED COSINE FILTER
40.8 KB Data
⊙ ZERO
X POLE
jω/10⁵
σ/10⁵
Σ(s)
1
2
3
-1
-2
-3
-4
-5
1.
2.
-1
-2
-3
N.S.L.

FIGURE 17

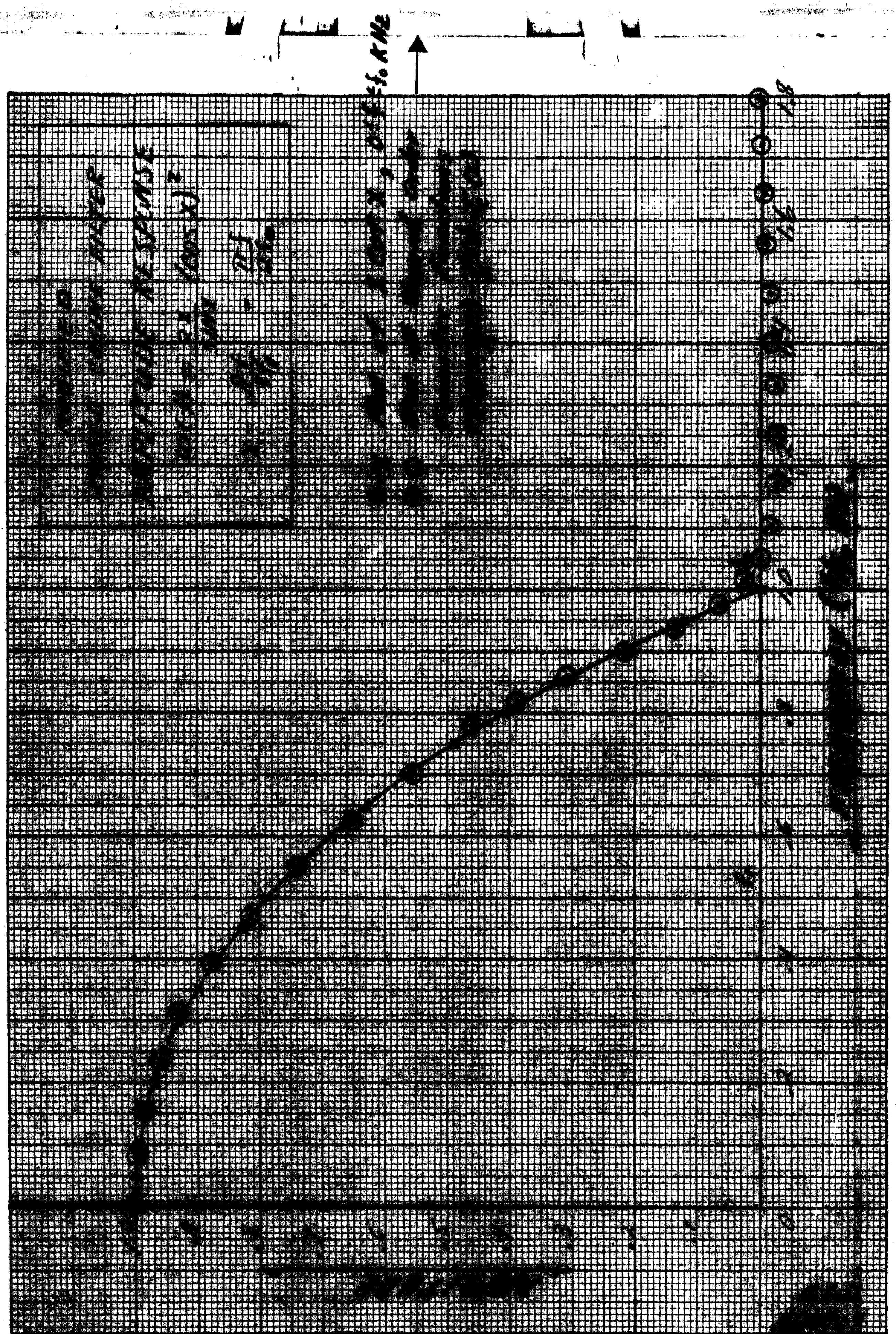


FIGURE 18

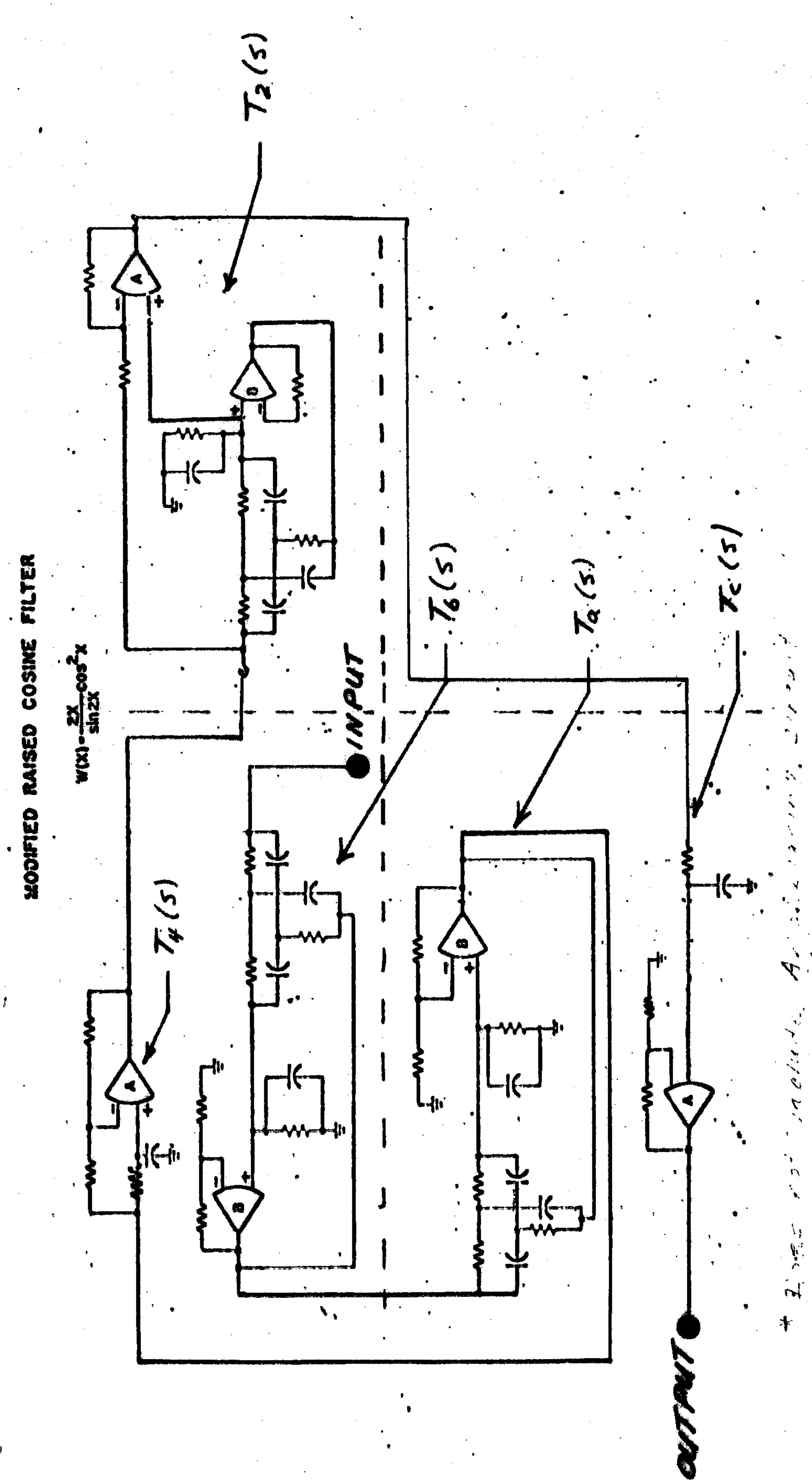
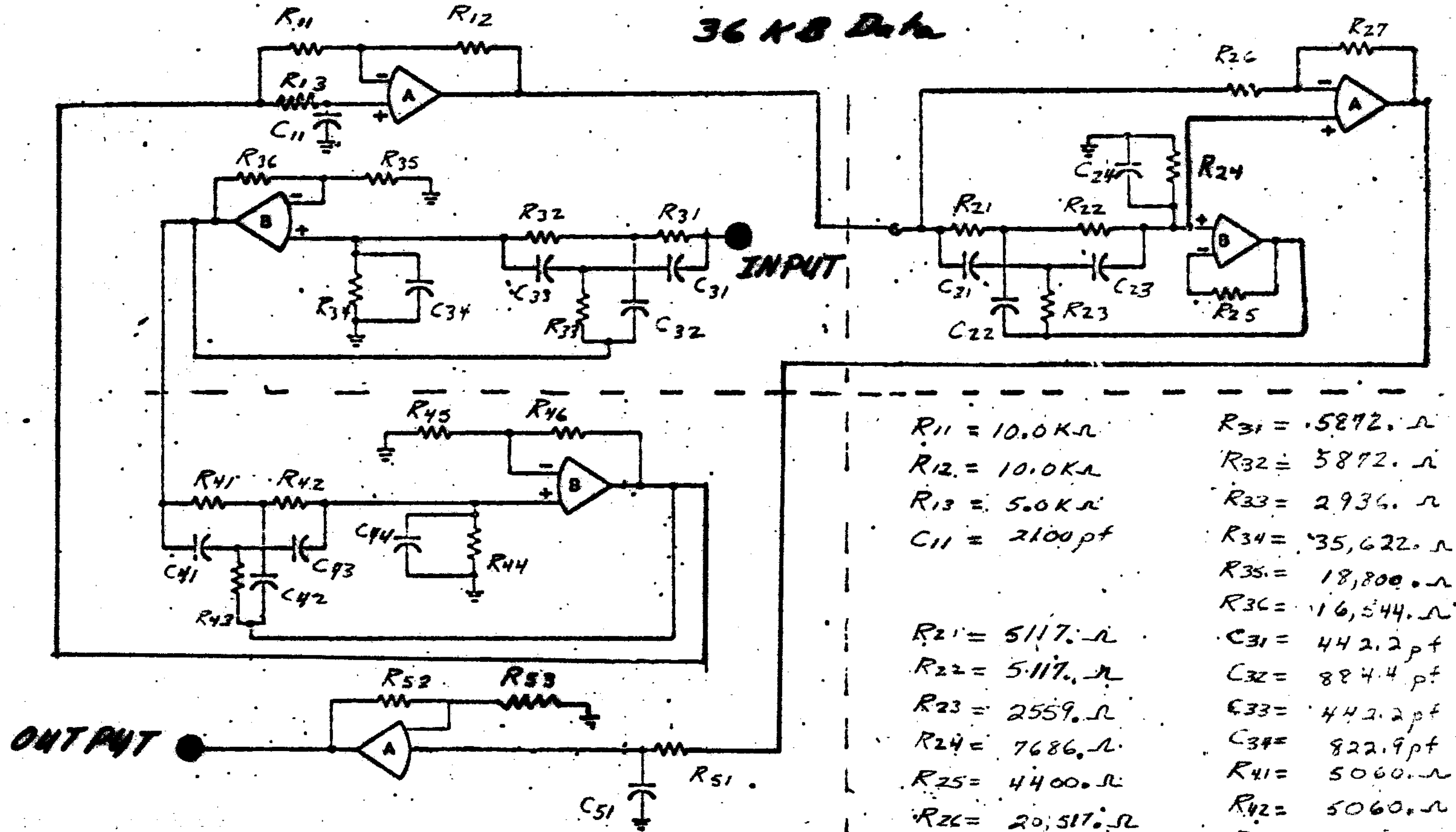


FIGURE 19

M.S.L.
9/14/67

MODIFIED RAISED COSINE FILTER

36 KB Data



* Does not include Amp biasing circuit

R_{11} = 10.0 KΩ
R_{12} = 10.0 KΩ
R_{13} = 5.0 KΩ
C_{11} = 2100 pf

R_{21} = 5117. Ω
R_{22} = 5117. Ω
R_{23} = 2559. Ω
R_{24} = 7686. Ω
R_{25} = 4400. Ω
R_{26} = 20,517. Ω
R_{27} = 5,601. Ω

C_{21} = 1442. pf
C_{22} = 2884. pf
C_{23} = 1442. pf
C_{24} = 960. pf

R_{31} = 5872. Ω
R_{32} = 5872. Ω
R_{33} = 2936. Ω
R_{34} = 35,622. Ω
R_{35} = 18,800. Ω
R_{36} = 16,544. Ω
C_{31} = 442.2 pf
C_{32} = 884.4 pf
C_{33} = 442.2 pf
C_{34} = 822.9 pf
R_{41} = 5060. Ω
R_{42} = 5060. Ω
R_{43} = 2530. Ω
R_{44} = 10,276. Ω
R_{45} = 31,554. Ω
R_{46} = 5,942. Ω

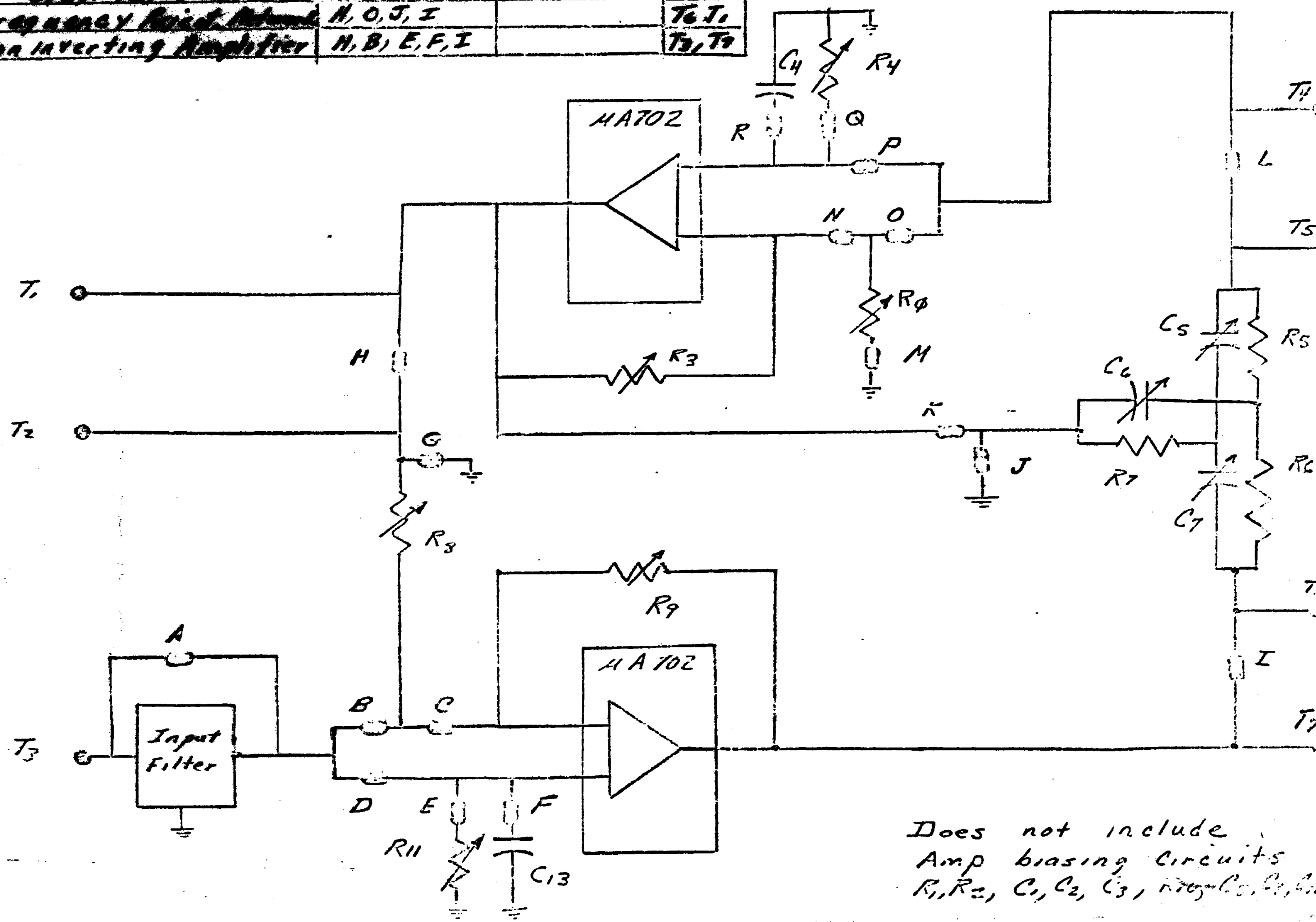
C_{41} = 829.4 pf
C_{42} = 1658.8 pf
C_{43} = 829.4 pf
C_{44} = 1866.1 pf
R_{51} = 4100 Ω
R_{52} = 3,221. Ω
R_{53} = 17.8 KΩ
C_{51} = 1165.8 pf

FIGURE 20

M.S.L.
9/14/67

Modified Active Filter

Filter Sections	Open Terminals	Short Terminals	Input [illegible]
Freq. Emphasizing Network	D, K, J, N, O, A		T_2, T_1
2nd order All Pass	B, E, F, I, J, N, M	$(T_3 T_4)$ $(T_2 T_6)$	T_6, T_7
1st order All Pass	A, B, E, F, G, I	$(T_2 T_3)$	T_2, T_7
Frequency Reject Network	H, O, J, I		T_6, T_1
Non inverting Amplifier	H, B, E, F, I		T_3, T_9



Does not include Amp biasing Circuits R_1, R_2, C_1, C_2, C_3, [illegible]

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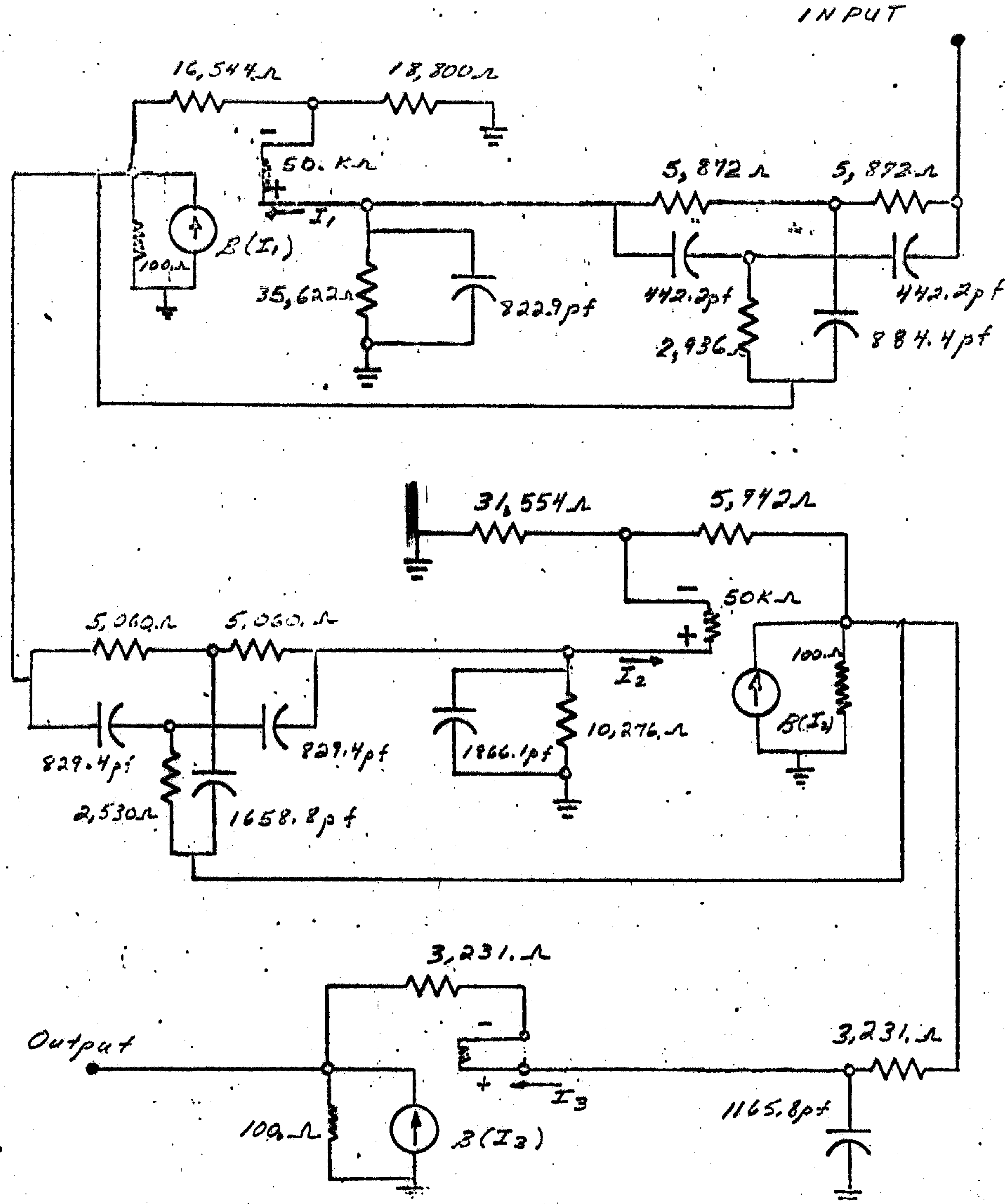
DRAWN

TITLE FIGURE 21
Modified Active Filter

BELL TELEPHONE LABORATORIES INCORPORATED

36 KB Data
Modified Raised Cosine Filter
ECAP CIRCUIT MODEL
of
Minimum Phase Sections



ISSUE	ENGR	TITLE	BELL TELEPHONE LABORATORIES INCORPORATED
9/14/67	M.S.L.	FIGURE 22	SHEET
	DRAWN	ECAP CIRCUIT MODEL	37

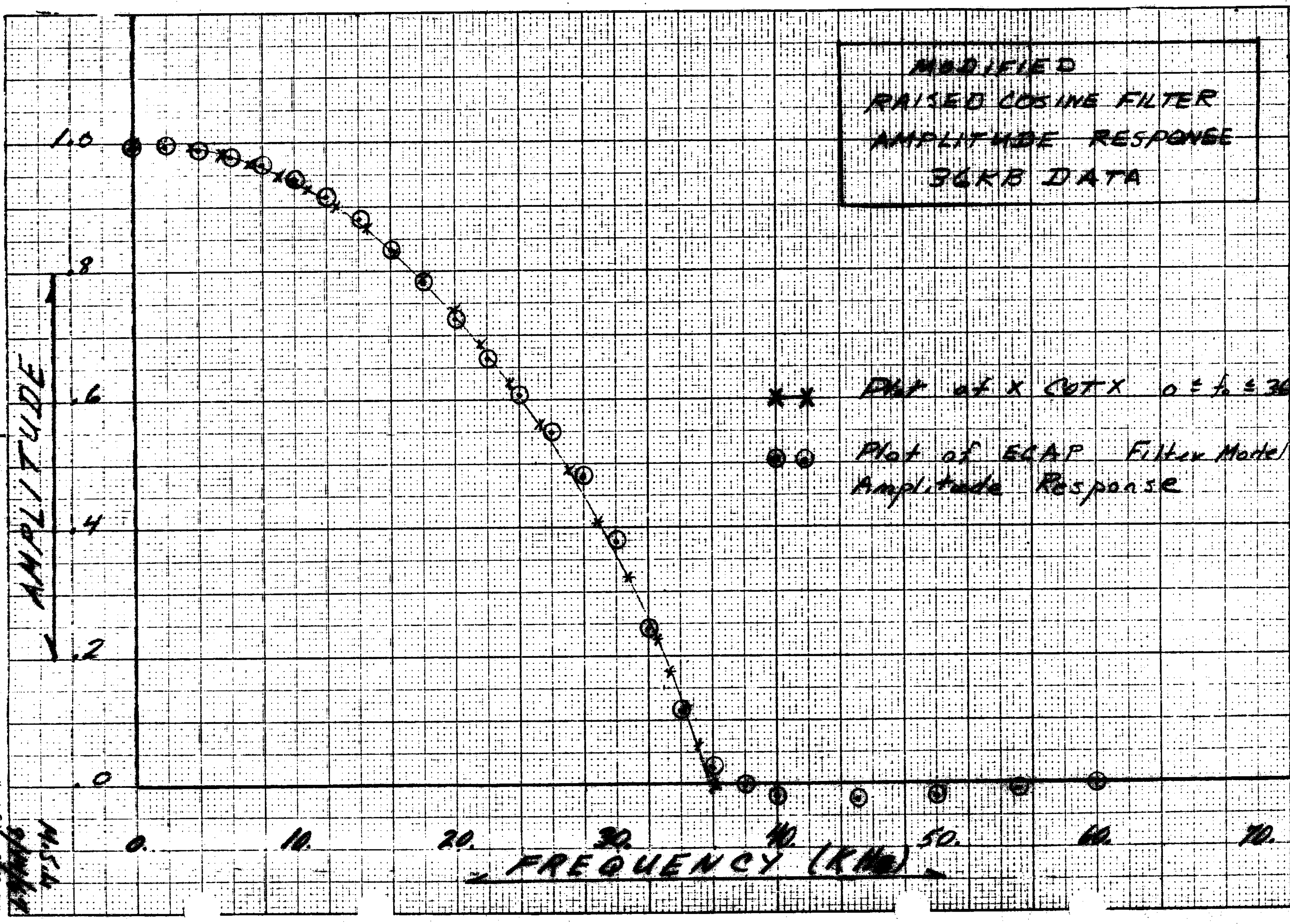

MODIFIED
RAISED COSINE FILTER
AMPLITUDE RESPONSE
36KB DATA
Plot of X Cot X
Plot of ECAP Filter Model
Amplitude Response
1.0
.8
.6
.4
.2
.0
AMPLITUDE
0.
10.
20.
30.
40.
50.
60.
70.
FREQUENCY (KHz)
E-1503 (3.58)
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FIGURE 23

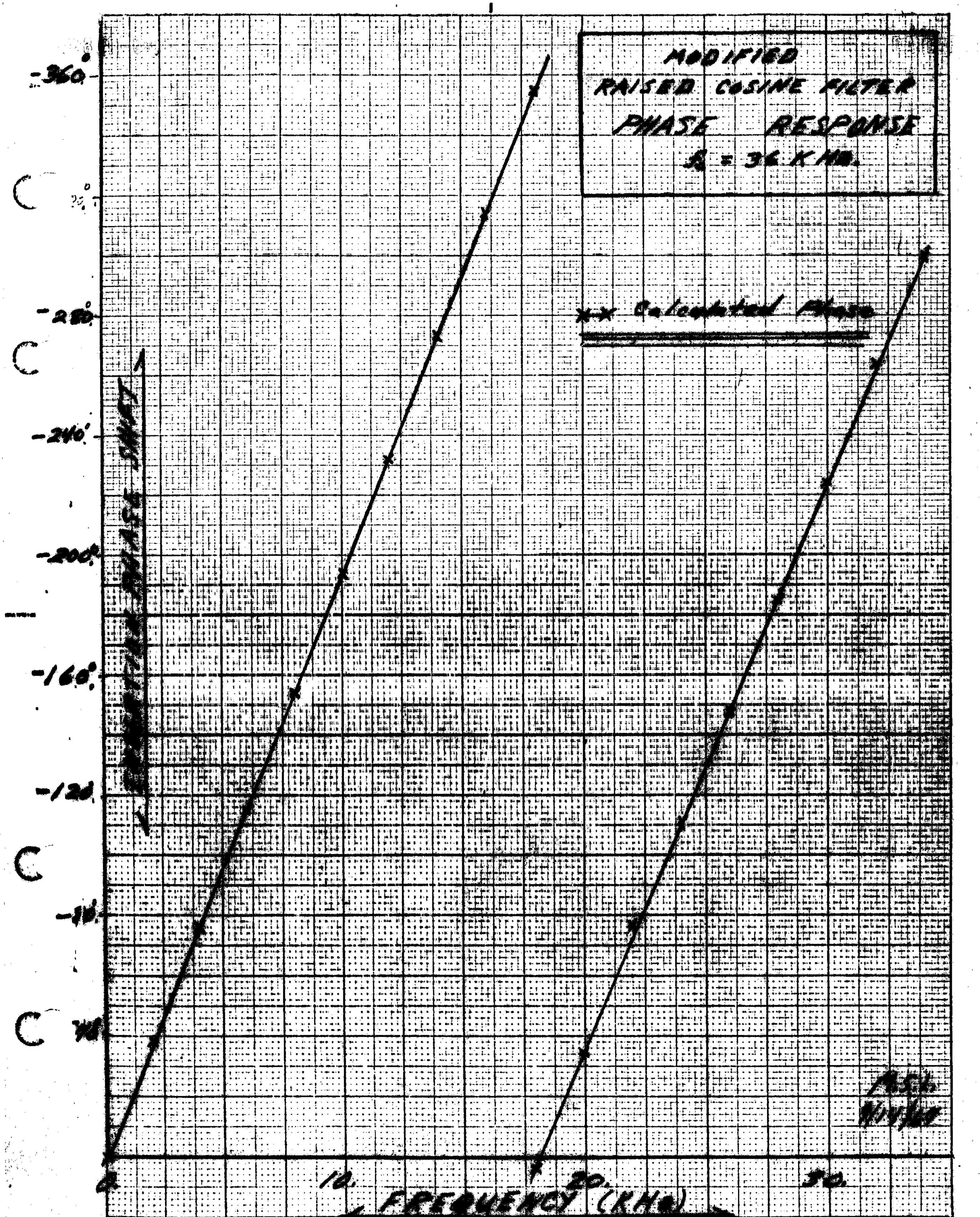
MODIFIED
RAISED COSINE FILTER
PHASE RESPONSE
= 36 KHz.
x-x Calculated Phase
-360°
-280°
-240°
-200°
-160°
-120
0
10.
20.
30.
FREQUENCY (KHz)
PHASE SHIFT
E-1963 (3-52)
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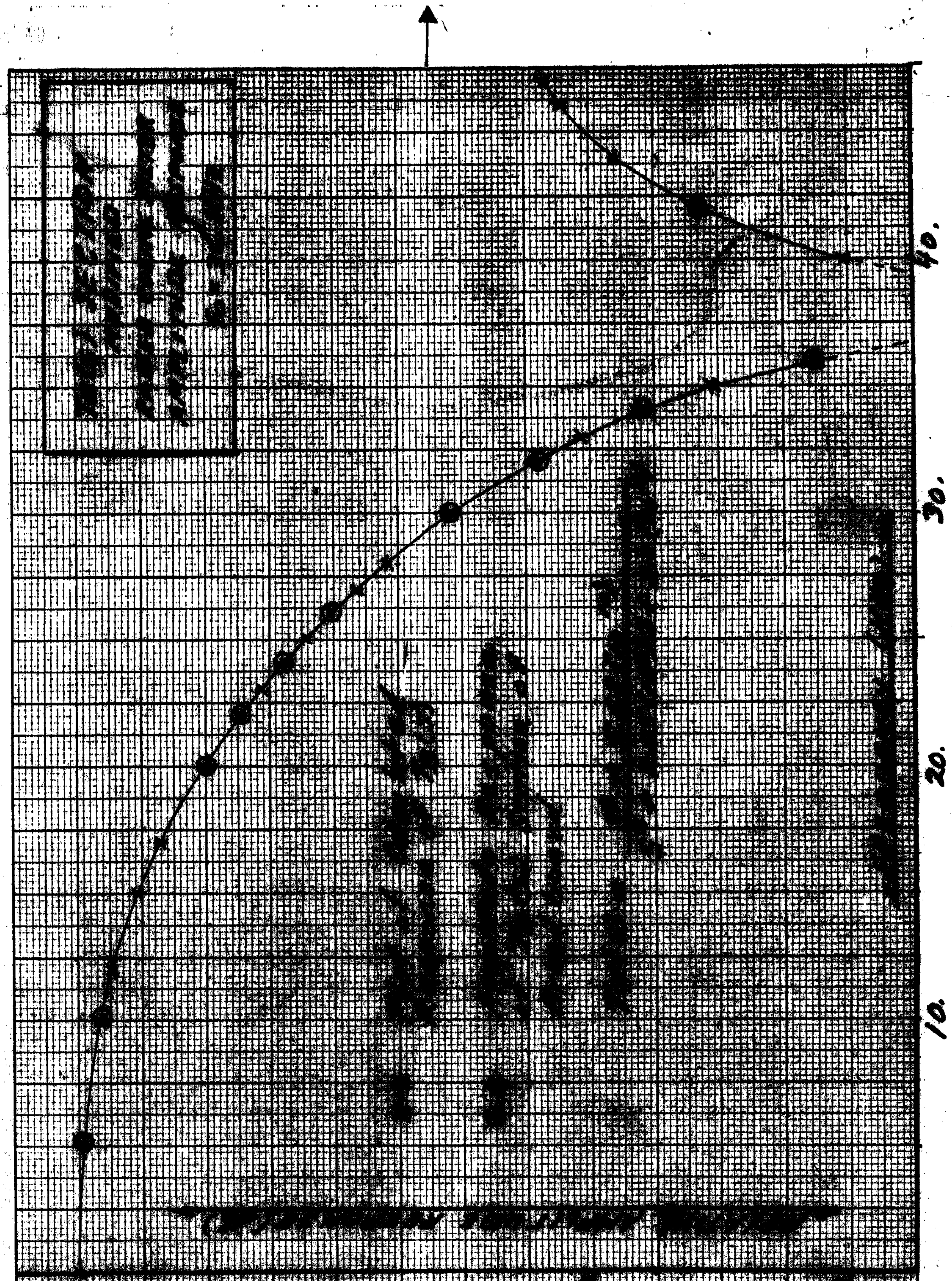
FIGURE 24

FIGURE 25



E-1563 (3-58)
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K & E CO. N.Y.

FIGURE 26

M.S.L.

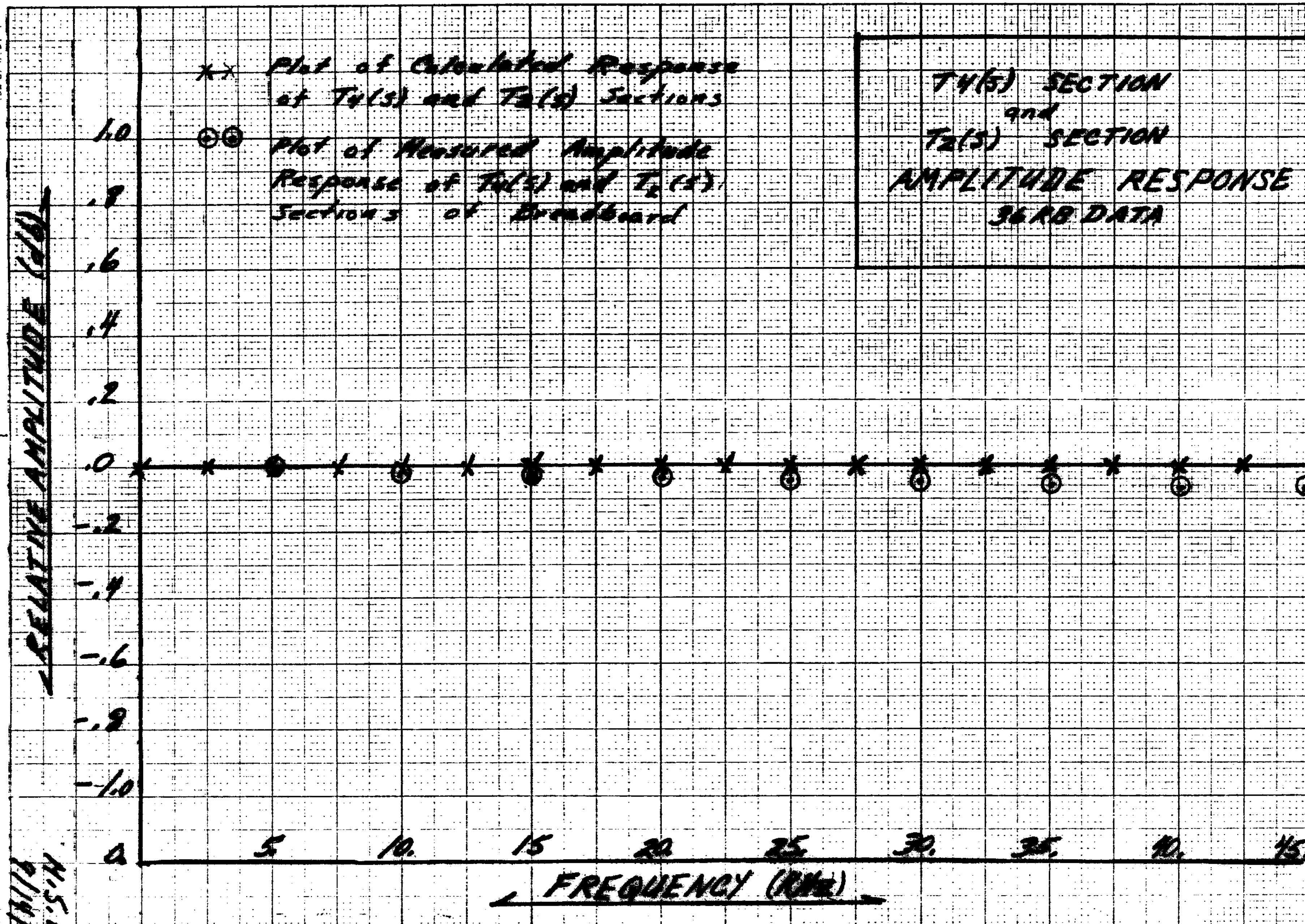

FIGURE 27

H.S.L.
9/14/67

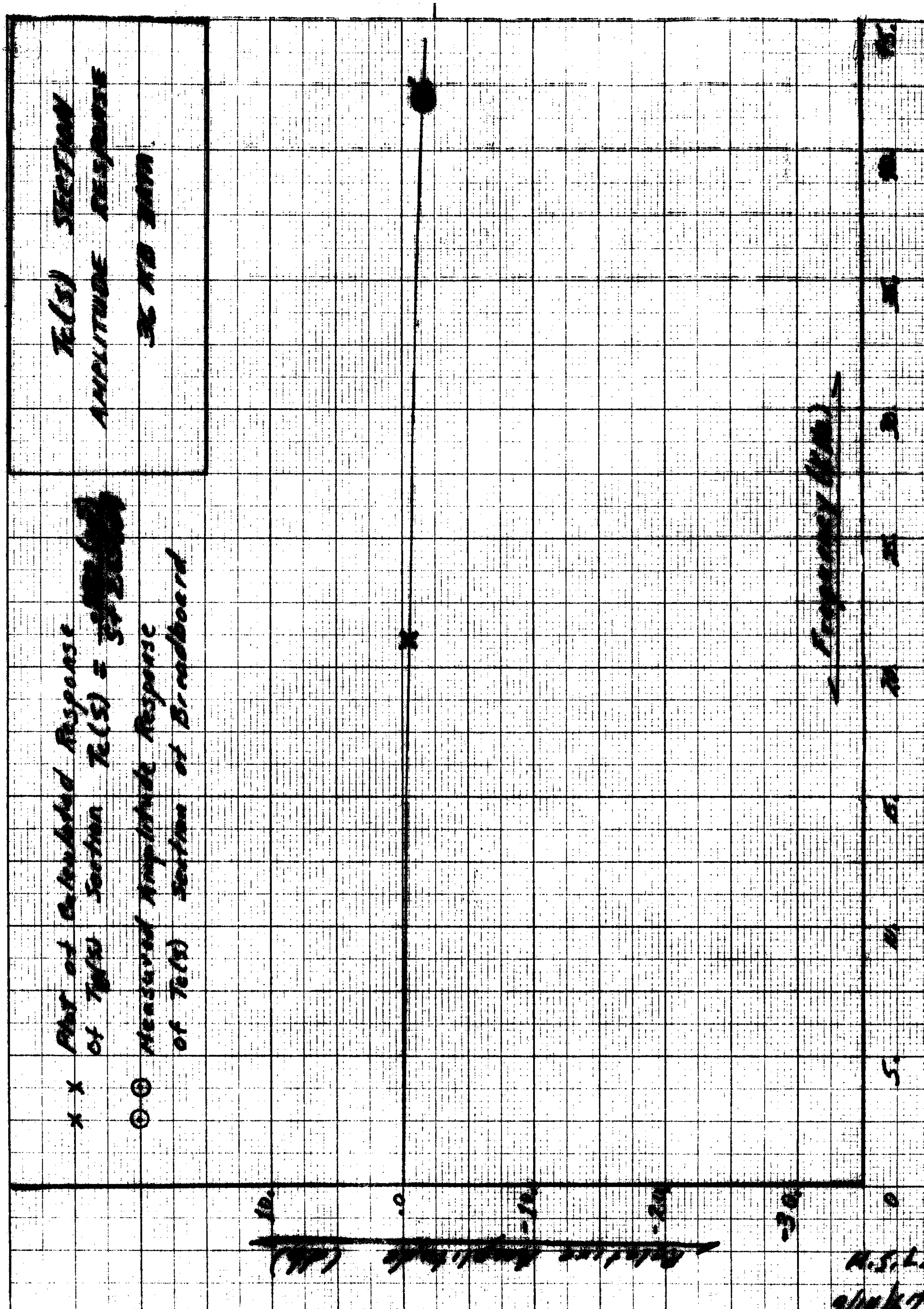
Tc(S) SECTION
AMPLITUDE RESPONSE
Plot of Calculated Response
of Tc(S) Section Tc(S) =
Measured Amplitude Response
of Tc(S) Section of Breadboard
10.
.0
-10.
-20.
-30.
0
5.
30.
Frequency
M.S.L.

Figure 28

E-1363 (3-58)
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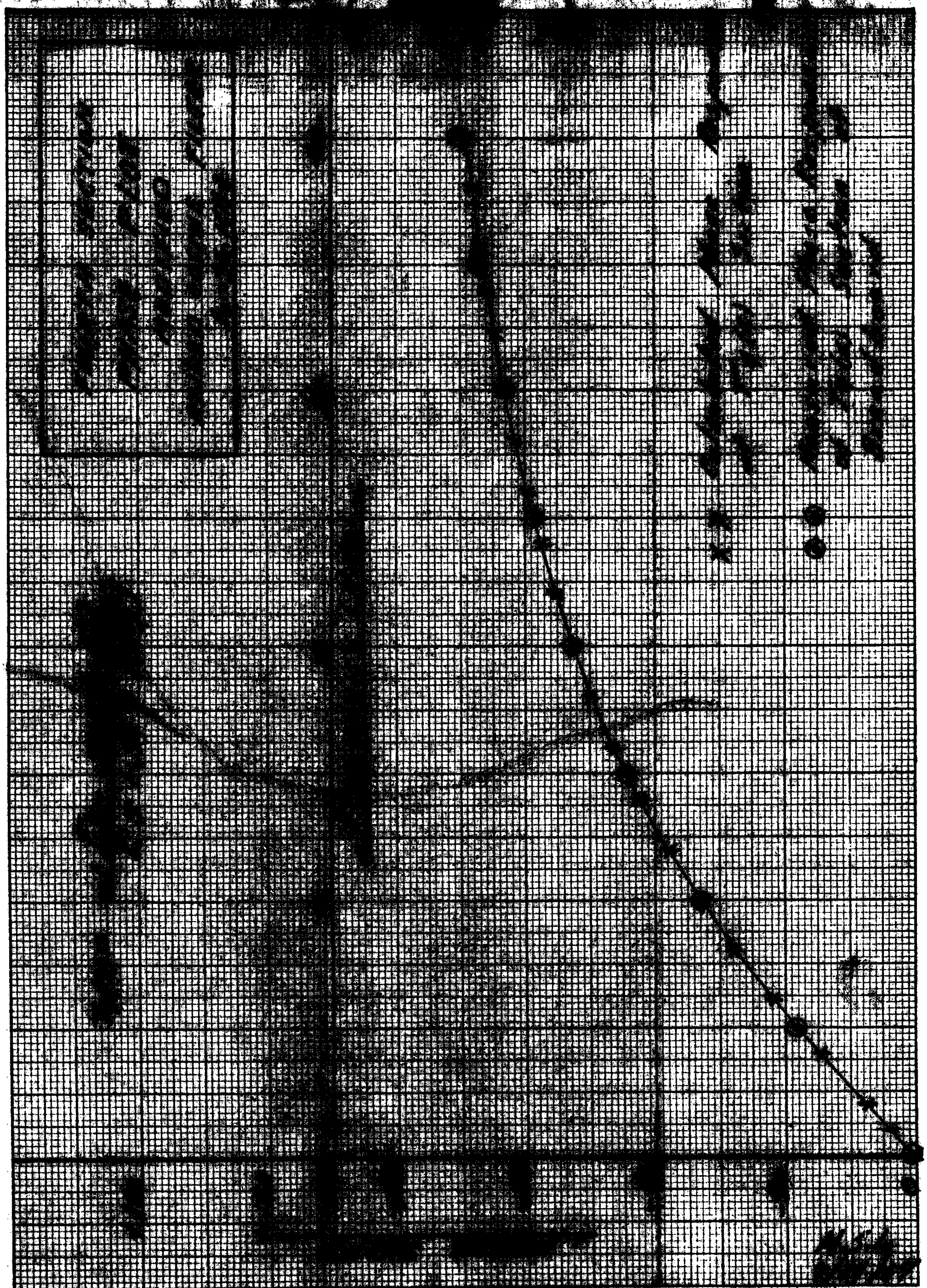
K & E CO. N.Y.

FIGURE 29



E-1563 (3-58)
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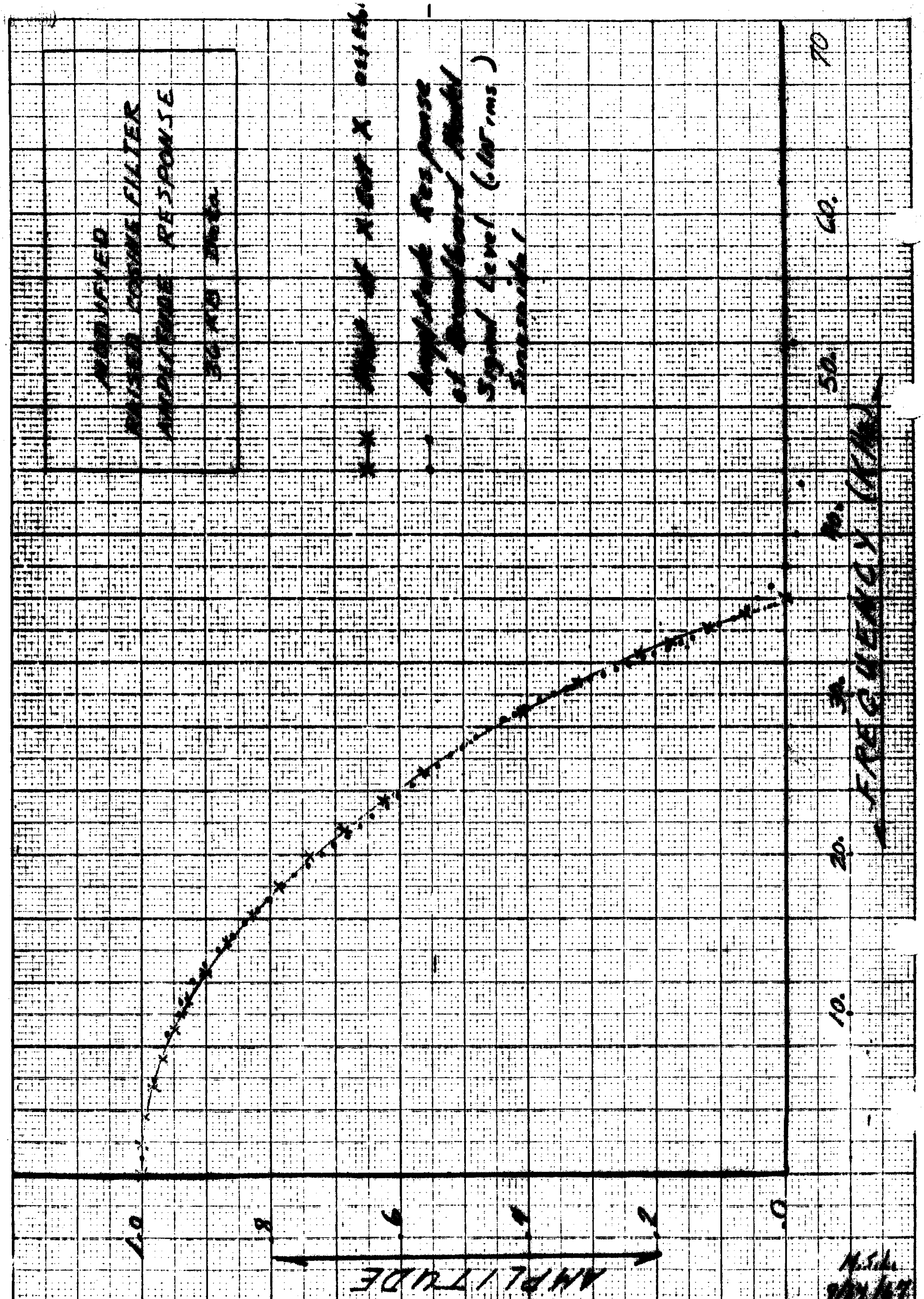
FIGURE 30



E-1863 (3-58)
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FIGURE 31

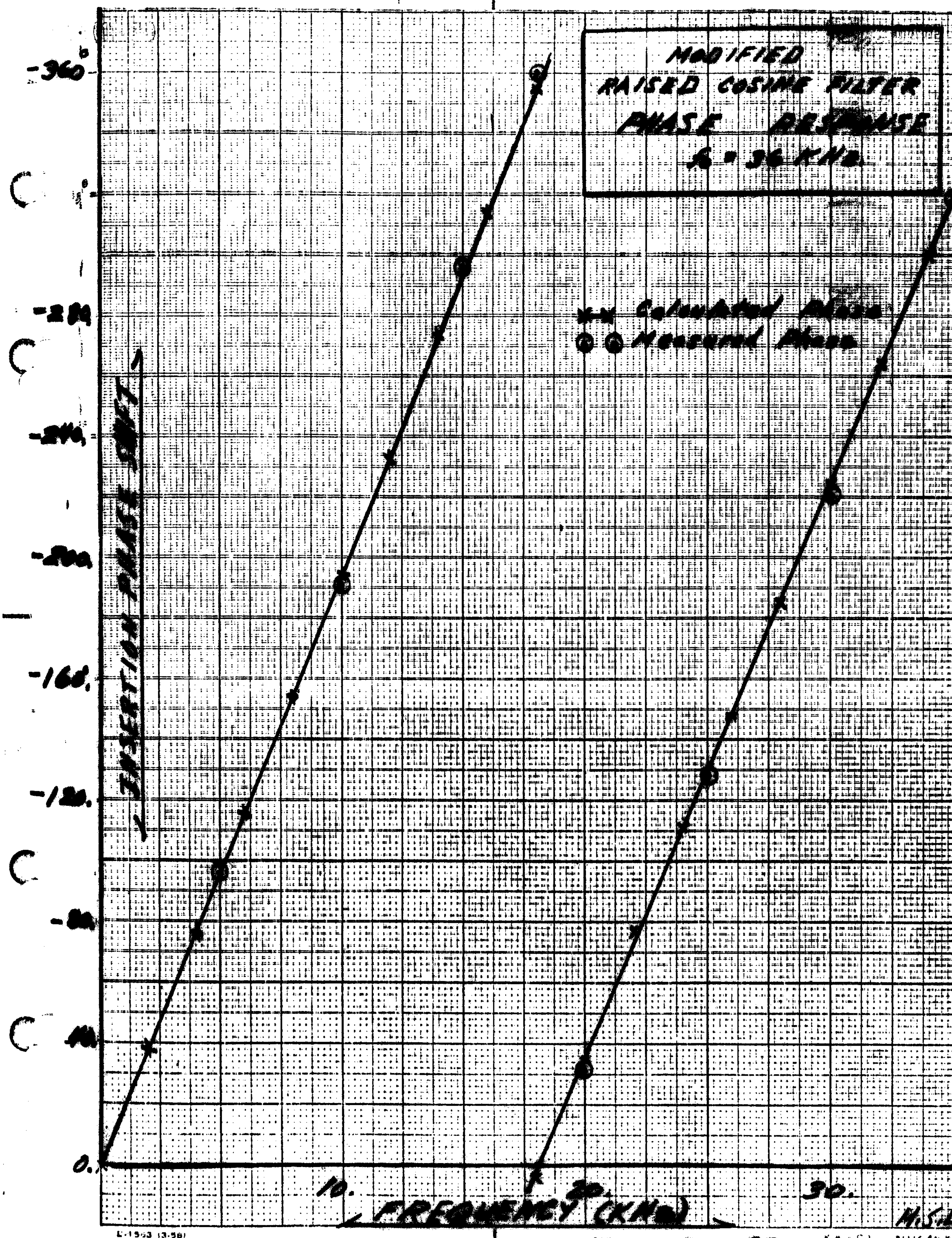


FIGURE 32

M.S.L.
9/14/67

Measured Characteristics
Breadboard Model 36KB Data
Modified Raised Cosine Filter
for 304 Data Set

D.C. Gain	1.0	
Offset Voltage	40mv	
Max. Signal Level (Sinusoidal)	1.0 v p-p	
Current Drain	15ma	
Power Dissipation	450mw	
Negative Supply Voltage	-6.0 v	
Positive Supply Voltage	+12. v	
Noise Level (Vin=0)	1.0 mv	Vout

ISSUE 9/14/67 | ENGR McSohe | DRAWN | TITLE FIGURE 33 Breadboard Model | BELL TELEPHONE LABORATORIES INCORPORATED | SHEET 48 | NO. OF SHEETS PER SET

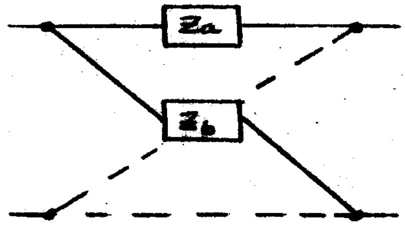


Fig 1A

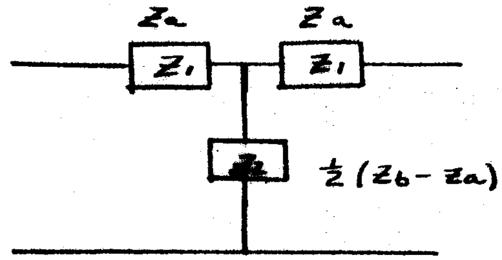


Fig 1B

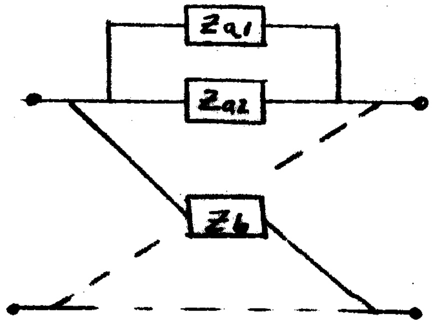


Fig 1C

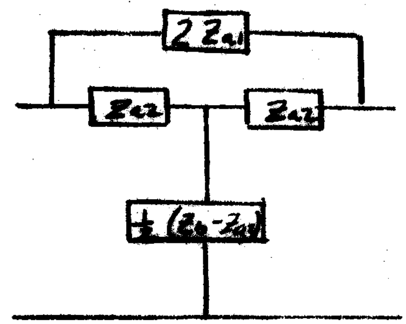


Fig 1D

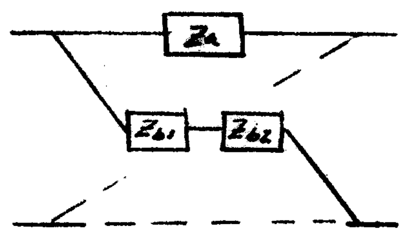


Fig 1E

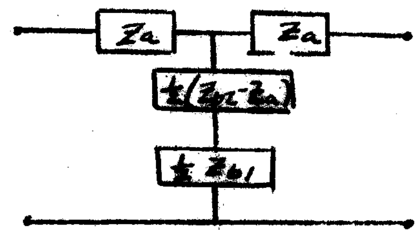


Fig 1F

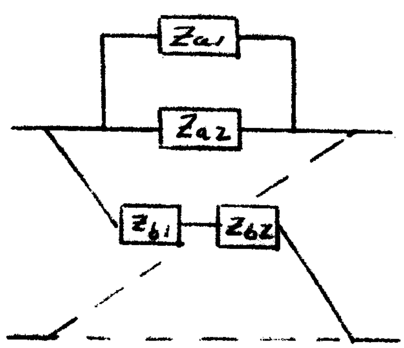


Fig 1G

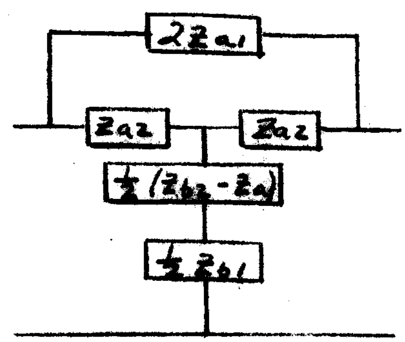
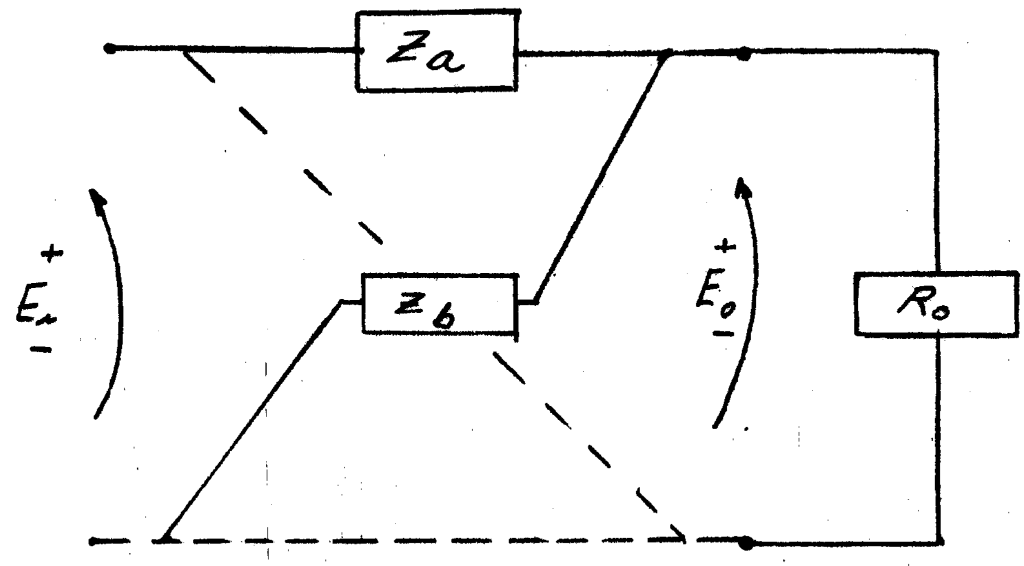


Fig 1H

ISSUE	ENGR / DRAWN	TITLE Appendix A Figure 1	BELL TELEPHONE LABORATORIES INCORPORATED	SHEET 49
			NO. OF SHEETS PER SET	



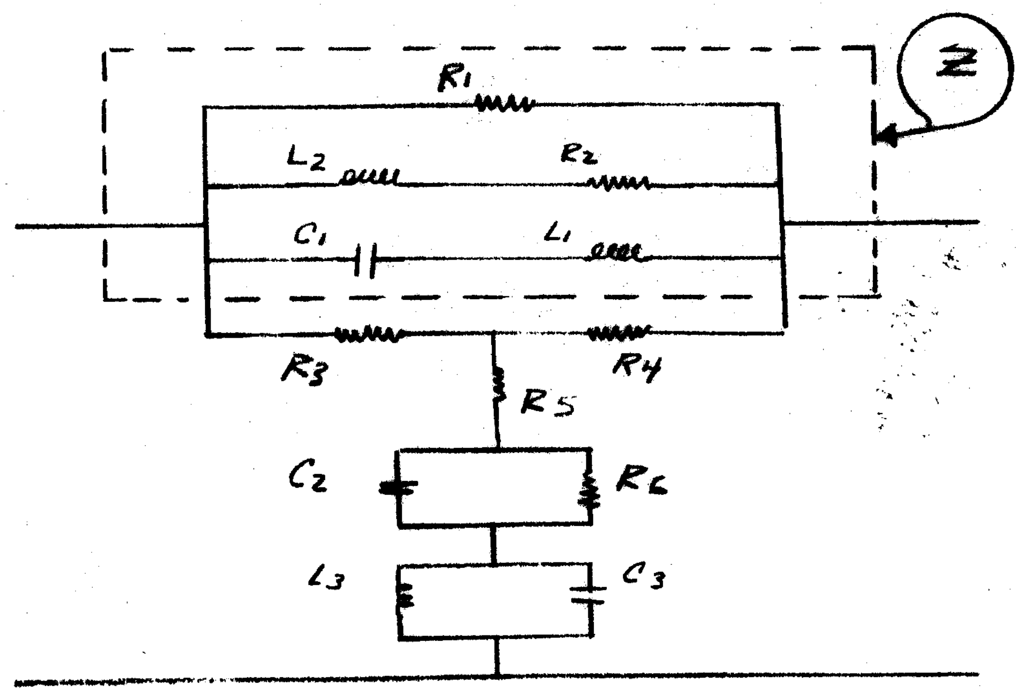
$$R_o = \sqrt{Z_a \cdot Z_b}$$

Constant Resistance
Symmetrical Lattice

$$T(s) = \frac{E_o}{E_i} = \frac{R - Z_a}{R + Z_a}$$

ISSUE | CHKD | DRAWN | TITLE Appendix B Figure 2 | SHEET 50

Appendix C



$$Z = R_1 \parallel (sL_2 + R_2) \parallel \left(L_1 s + \frac{1}{C_1 s}\right)$$

$$Z = \frac{R_1 L_2 L_1 s^2 + R_1 R_2 L_1 s + \frac{R_1 L_2}{C} + \frac{R_2 R_1}{C}\left(\frac{1}{s}\right)}{L_2 L_1 s^2 + \left[R_2 L_1 + R_1(L_2 + L_1)\right]s + \left(R_2 R_1 + \frac{L_2}{C}\right) + \frac{(R_1 + R_2)}{C}\left(\frac{1}{s}\right)}$$

$$T(s) = \frac{1}{1 + \frac{Z}{R_0}}$$

$$T(s) = \frac{L_2 L_1 s^2 + \left[R_2 L_1 + R_1(L_2 + L_1)\right]s + \left(R_2 R_1 + \frac{L_2}{C}\right) + \frac{R_1 + R_2}{C}\left(\frac{1}{s}\right)}{\left(1 + \frac{R_1}{R_0}\right)L_2 L_1 s^2 + \left[R_2 L_1\left(1 + \frac{R_1}{R_0}\right) + R_1(L_2 + L_1)\right]s + \left[R_2 R_1 + \frac{L_2}{C}\left(1 + \frac{R_1}{R_0}\right)\right] + \left[\frac{R_2}{C}\left(1 + \frac{R_1}{R_0}\right) + \frac{R_1}{C}\right]}$$

ISSUE	ENGR / DRAWN	TITLE	BELL TELEPHONE LABORATORIES INCORPORATED
		Appendix C	NO. OF SHEETS PER SET — SHEET 51