THE RIMO FILTER

BY

RICHARD THOMAS MODAFFERI

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ABSTRACT

Up to the present time, there has existed no general method for obtaining the pole locations of minimum-phase constant time delay filters of desired selectivity. Since constant time delay filters are necessary for low distortion FM transmission, and minimum-phase filters are easy to construct and align, a general method for locating the poles of minimum-phase constant time delay filters would be of considerable importance. Presented in this paper is a procedure for locating the poles of minimum-phase constant time delay filters of desired selectivity, using a FORTRAN digital computer program. Two experimental FM receivers were built to test the new filter characteristic, and the performance of these receivers is discussed.

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INTRODUCTION

With the advent of stereo FM broadcasting, very stringent requirements have been set for the design of a suitable receiver. In particular, one important aspect of FM receiver design - the IF amplifier - has been largely neglected in tuners and receivers intended for the consumer market. For the most part, these circuits fall into a general stereotype consisting of amplifier stages which are permitted to act as limiters on strong signals combined with tuned circuits of insufficient selectivity - a sacrifice necessary to obtain nearly constant time delay to the signal. Since many shortcomings in performance which arise in commercial tuner and receiver designs can be traced at least in part to the IF amplifier, it might be that the application of some new ideas would cause some improvement in FM IF amplifier performance. One factor that is of considerable importance in any new design is the cost. New designs must be commercially feasable: economical in materials, easy to construct and align, and reliable.

In seeking a means to improve on the solution of the FM IF amplifier problem, the writer has devised a new class of linear-phase filters which will be the main subject of this paper. The study will continue with a discussion of a unique FM IF amplifier system designed to make most effective use of the new filter characteristic. Consideration of the use of the new IF amplifier in an experimental FM stereo receiver will be reserved for the final sections.

IF AMPLIFIER BANDPASS CHARACTERISTICS

Originally, some quite ordinary design approaches to the FM IF amplifier problem were investigated. Initially a minimum phase filter amplifier of nominally constant time delay based upon cascaded synchronously tuned stages was constructed. Next an amplifier using a system of stagger-damped stages giving a Bessel characteristic was tried. Both were rejected because of insufficient selectivity.

Another design effected a compromise by using a selective minimum-phase characteristic, such as Butterworth, which had fair phase characteristics with good enough selectivity to provide good alternate channel reception in most cases.[1]

The Butterworth tuner gave rather good performance[2] and probably justifies the lack of initiative that has been evident in commercial tuner designs - most of which use some type of flat-amplitude minimum-phase filter amplifier. But the Butterworth tuner still suffered from both inadequate selectivity and serious overloading of the IF amplifier on strong signals.

One of the well known characteristics of a selective, flat-amplitude minimum-phase filter is that the time delay increases from the mid-band toward the band edges. It occurred to this writer that if a single tuned circuit is placed in cascade with the aforementioned

1. The writer used this approach in an earlier paper, Ref. 1.

2. Performance data and specifications of this early tuner, extracted from Ref. 1, appear in the appendix.

filter and tuned to its midband frequency, some delay equalization will be obtained as qualitatively shown in Fig. 1.

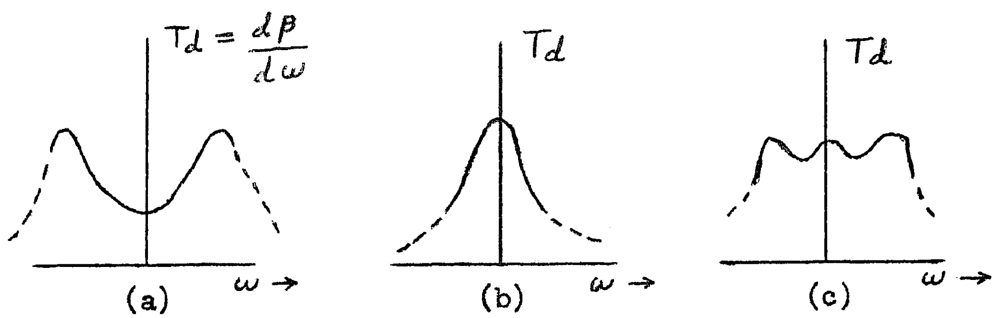


Fig. 1. Delay equalization of a bandpass filter. (a) Time delay for a hypothetical bandpass filter, (b) Time delay for a single tuned circuit, and (c) Time delay for the bandpass filter and single tuned circuit in cascade.

The concept outlined in Fig. 1 can be expanded. The question was asked: If the poles of a minimum-phase filter can be adjusted to give any desired amplitude shape, might not they also be adjustable to give any desired phase response? In particular, if the pole locations of linear-phase all-pole filters of any desired selectivity could be determined, a whole new approach to the FM IF amplifier design problem would be generated.

There has existed no general method for easily obtaining the pole locations for minimum-phase constant time delay filters of any desired selectivity. Of the known filters in the minimum-phase class with nominally constant time delay - Bessel, Gaussian, and Butterworth-Thompson - the problem is either one of insufficient selectivity or of less than optimum time delay characteristics. Highly selective filters of constant time delay may be realized by adding an all-pass delay equalizer to a Butterworth or Legendre filter, but the physical construction and alignment of these all-pass delay equalizers at 10.7 MC (the FM IF amplifier frequency) is so nearly impossible as to rule out any consideration for their use in a commercially feasable FM receiver.

THE RIMO FILTER

Presented in this paper are several of a new class of minimum-phase filters, having nominally constant time delay and moderately flat amplitude response inside their passbands, and high selectivity outside their passbands. The pole locations for these filters were obtained by computer solution, and some of the resulting pole constellations are found to allow the design of a selective, low distortion FM IF amplifier.

The basic concept of the Rimo[3] filter is simple but requires a high speed digital computer to obtain the pole locations. Applying the Rimo filter concept begins with the placing of some number of poles in the S-plane and adjusting from just one to all of these poles until minimum delay error occurs in the passband. An almost infinite variety is then possible, with Fig. 2 on page 5 showing three possibilities. In filters (1) and (2), poles (X) form a standard minimum-phase filter, and poles (+) may be considered as a separate delay equalizer: These are "hybrid" Rimo filters. In (3), all the poles were adjusted to give minimum delay error; this is a "pure" Rimo filter.[4]

3. A name generated by taking the first two letters from RIchard MOdafferi.

4. Pole locations for "pure" Rimo filters approximate those for Bessel filters, with the two tending to become more nearly identical as the number of poles increases.

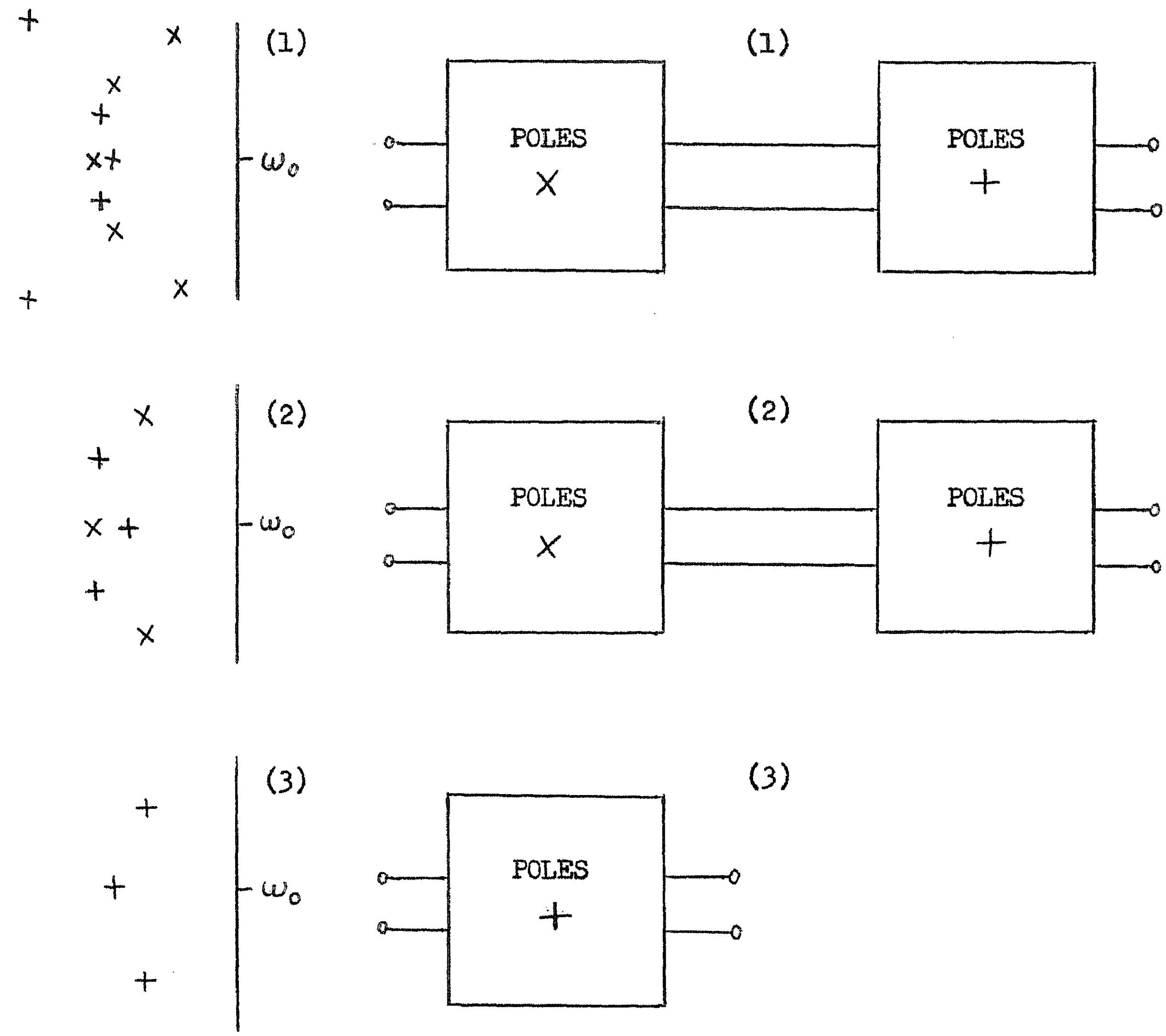


Fig. 2. Three Rimo filters. In equalizing the time delay in the passband, poles (+) were moved and poles (×) were held fixed. Although the poles × and + of filters (1) and (2) are shown split into two definite sections (which may be considered as a filter plus a delay equalizer), this is not mandatory. The Rimo filter may be realized in any manner particular to minimum-phase filters.

A general computer program has been written in IBM Fortran to allow any number of poles from four to twenty to be placed in the S-plane. Up to ten of these poles may be fixed, and up to ten of them may be movable to give minimum delay error. For example, the designer may select a five-pole Butterworth filter, add five more poles, and locate the ten poles of a hybrid Rimo filter by using the computer to adjust the five added poles to equalize the delay of the Butterworth filter. When the pole locations have been determined, the filter may be realized by any synthesis methods the designer chooses.

BASIC THEORY OF THE RIMO FILTER COMPUTER SOLUTION

In order to obtain a linear-phase characteristic from an arbitrary number of poles placed in the S-plane, a computer program is required whose operation is entirely automatic and convergent; i.e., the computer must accept the given poles and move them quickly without equivocation into what should be one and only one optimum constellation. Some thoughts on this idea will now be presented.

Given any number of poles in the S-plane, one may obtain minimum delay error by moving all of the poles out to infinity. The resulting filter then could be realized as a ladder structure consisting of series open circuits and shunt short circuits - a realization of no practical value. Thus the first consideration in writing the computer program is that of keeping the given poles clustered symmetrically about the mid-band frequency so that some kind of selective filter will result. This is most easily accomplished by specifying the mid-band time delay and holding this value constant during execution of the program, automatically forcing all of the poles to remain near the mid-band frequency.

If one plots the phase response of a hypothetical narrow band minimum-phase bandpass filter, and superimposes on this curve a straight line drawn tangent to the phase curve at the mid-band frequency, the result in Fig. 3 may be obtained.

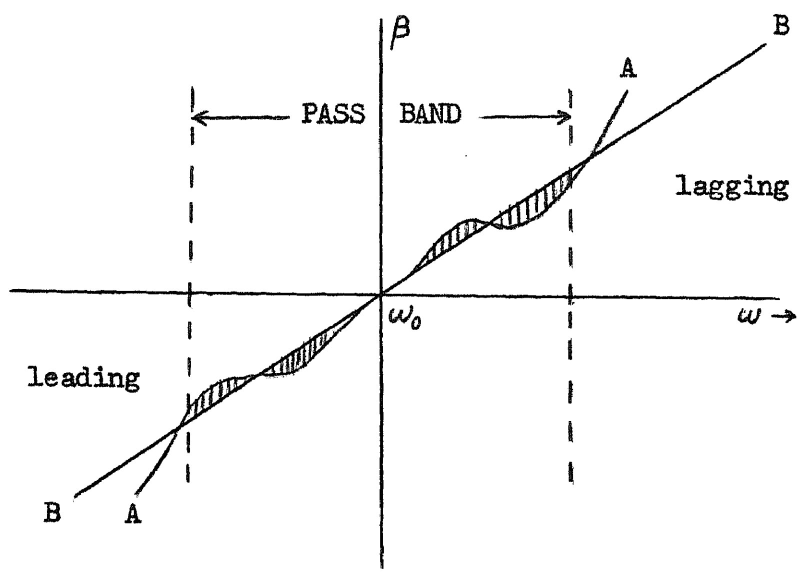


Fig. 3. Phase response of a bandpass filter having poor phase linearity. Curve (A) is phase characteristic of filter, line(B) is drawn tangent to phase curve at the mid-band frequency. The shaded area between (A) and (B) is a measure of the phase error.

If a computer program can be set up such that the shaded area in Fig. 3 is automatically reduced as poles are moved, the problem will be solved, since a filter having a straight line phase shift will have constant delay.

OUTLINE OF THE COMPUTER SOLUTION

The method of the computer program will be shown by consideration of a simple example. Given the three poles of Fig. 4, let them be adjusted to give minimum delay error in the passband.[5] The computer will first calculate the mid-band time delay for the three poles. This value of time delay is then stored and any subsequent pole movements are controlled in such a manner as to hold this initial time delay essentially constant. Next, the phase shift for the three poles is calculated at frequencies along the $j\omega$ axis beginning at the mid-band frequency and ending at an arbitrary point selected by the programmer - this ending point usually being just beyond the imaginary coordinate of the last poles (P1 and P3 of Fig. 4).

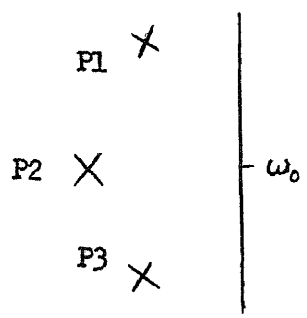


Fig. 4. Three poles to be adjusted by the computer to give minimum delay error.

The values of phase shift are then compared with those values obtained from a straight line drawn through the phase characteristic for the initial pole positions, as in Fig. 4. With the lines A and B of Fig. 3 determined in the computer, it next calculates the magnitude of the shaded area between them and stores this number.

Now a pole is moved. First, the middle pole is moved a small distance along the real axis with other poles remaining fixed at their initial locations. Then the shaded area is recalculated. If it

5. The result will approximate an $n = 3$ Bessel filter.

is less, indicating lower phase error, the pole is moved again in the same direction until the value of the area passes through a minimum. Upon passing through the minimum, the pole is moved back to the location giving minimum delay error and left at this point.
If upon the initial movement of pole P2 in the real direction the area had become larger rather than smaller, the pole movement would have been reversed and a minimum sought.

Next, poles P1 and P3 are moved in the real direction as a conjugate pair until the area function is again minimized. Following this, poles P1 and P3 are moved in the imaginary direction to seek an area minimum. Now all three poles have been moved in all possible directions to minimize the delay error. However, due to interactions between the poles upon the delay error, the entire process is generally repeated for a number of complete cycles.

Usually, four or more complete cycles of pole movement will complete the minimization of the delay error. How quickly the solution is arrived at depends on many factors, including how close to the optimum the starting pole constellation was, and for what percent of the passband a linear phase response is desired.

There exist refinements in the program which allow the operator to exercise some control over the results. The initial value of pole movement increment is adjustable. Assuming that a rough solution is required, the poles may be adjusted in large steps to arrive quickly at a result good enough for an evaluation.

The programmer may decide to equalize the delay over the whole passband, or choose equalization near the mid-band frequency only - the latter giving somewhat better amplitude characteristics. Using the program, any known all pole filter may have poles added to it and then have these added poles adjusted to give minimum delay error to the combination. The program is limited, however, to the poles of minimum-phase filters, although modifications to include poles and zeros of nonminimum-phase filters are not impossible.

DESIGN OF RIMO FILTERS USING THE COMPUTER PROGRAM

Introduction

Realization of a Rimo filter begins with choosing the desired selectivity. A given selectivity can be satisfied by several pole constellations, but by referring to the normalized data in the appendix, the approximate number of poles required for linear-phase filters of desired selectivity may be determined by examining the amplitude responses for the tabulated Rimo filters. If the design criteria can be met by one of the pole plots in the appendix, the location of the poles is thus finished and the realization of the filter can proceed to any synthesis method the designer chooses.

If the requirements cannot be met by one of the pole plots in the appendix, or if the designer wishes to equalize the delay of some filter he already has, the computer program will have to be used.

Explanation of the Computer Program

During the forthcoming discussion of the actual programming of the computer to design a Rimo filter, the program and its flow chart will be covered in detail.[6] A through understanding of the operation of the program is essential in order for one to achieve maximum results.

6. The program and flow chart appear in Appendix, pages 7 to 18.

Table no. 1 below lists the variables which are used by the computer in working the program. Some of these variables are used by the programmer in initializing the problem; others are used only by the computer in working out the program. This table should be referred to as the discussion of the program and its flow chart progresses.

TABLE 1.

(a) Variables Used by the Programmer

```
NF............number of fixed poles
NV............number of movable poles
I.............equal to zero for odd number of fixed poles
              equal to one for even number of fixed poles
NI............equal to zero for odd number of movable poles
              equal to one for even number of movable poles
MOOD
DELL
COW   .........used collectively to control pole movements
MOO

XX(NN)
YY(NN)........dimensioned array for the movable poles

X(N)
Y(N)..........dimensioned array for the fixed poles

FB............area weighting function
CONST.........area weighting function
REFER.........initial value for weighted area
```

(b) Variables Used by the Computer Only

```
INDEX.........cumulative number of pole movements made
POSER.........maximum positive phase error, radians
ERNEG.........maximum negative phase error, radians
KOSFQ.........frequency of maximum positive phase error
NEGFQ.........frequency of maximum negative phase error
```

TABLE 1, CONTINUED

ERFNC..........weighted area between linear-phase line and filter phase curve.
FEE............phase angle to the fixed poles.
FEEE...........phase angle to the movable poles.
MOD............control variable used in locating point of minimum phase error during movement of a pole.
M..............variable controlling computed GO TO.
N..............index on dimensioned variable for fixed poles.
NN.............index on dimensioned variable for movable poles.

NE.............dummy variable used to set value for NSFP.
NNE............dummy variable used to set value for NSVP.
NSFP...........equal to one for odd number of fixed poles, equal to two for even number of fixed poles.
NSVP...........equal to one for odd number of movable poles, equal to two for even number of movable poles.
DEL............actual distance a pole is moved in S-plane.
INDIX..........number punched in output data. Gives total number of pole movements accumulated by computer when a pole is located at point of minimum delay error.

ERRA,...
...ERRU........departure from linear phase, in radians, at normalized frequencies of 5, 10, 15....100 radians/second.

MM.............dummy variable used to control exit of computed GO TO loop.
K..............fixed point frequency variable.
F..............floating point frequency variable. Always equal numerically to K.
ANG(K).........phase angles to all poles at frequencies K for all K from 1 to 100.
FE(K)..........phase angles to fixed poles only at frequencies K for all K from 1 to 100.
ANGL...........phase angle to all poles at frequency K equal to one only. Also equal to the numerical value of the normalized time delay in seconds for the mid-band frequency.
ERR(K).........phase error as departure from linear-phase for all K from 1 to 100.
DELTA..........dummy used to accumulate summing of the weighted errors. (see ERFNC below)
ERFNC..........weighted area function resulting from the continued summing of DELTA.
JERR(K)........ERR(K) multiplied by a thousand. Used to control IF statement which in turn controls output data punched for NEGFQ, ERNEG, KOSFQ, and POSER.

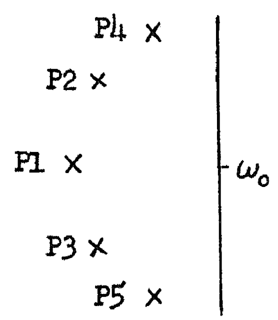
TABLE 1, CONTINUED

KLUNK..........controls direction of initial movement of a pole; reverses movement direction if initial movement causes an increase in phase error.

COW
MOO............used together to fix the number of pole movements taken during full execution of the program.

The logic of the computer program will be most easily understood if the above table is used in conjunction with the flow chart in following the program.

Consideration of a specific example will show how the program operates: five movable poles will be adjusted to equalize the delay of a five-pole minimum-phase filter. Given in Fig. 5 below are the poles of a five-pole Butterworth function, taken from Ref. 2, page 331.



P4	0.309 + j0.951
P2	0.809 + j0.588
P1	1.000 + j0.000
P3	0.809 -j0.588
P5	0.309 -j0.951

Fig. 5. Pole locations for a five-pole Butterworth function. (L.H.P. poles only)

Before insertion into the computer, the poles must be normalized such that the imaginary parts of the outermost poles (those farthest from the mid-band frequency) have an absolute value at or slightly below 100.000.[7] This is most conveniently done by multiplying the real and imaginary parts of all poles in Fig. 5 by 100.000 with the resulting values appearing in Table 2 below.

TABLE 2

Fixed poles scaled for insertion into the computer

X(1)......100.000	Y(1)...... 0.000
X(2)...... 80.902	Y(2)...... 58.779
X(3)...... 80.902	Y(3)......-58.779
X(4)...... 30.902	Y(4)...... 95.106
X(5)...... 30.902	Y(5)......-95.106

A guess based on a graphical study of this pole configuration led to placing the five movable poles as follows:

TABLE 3

Movable poles scaled for insertion into the computer

XX(1)......100.000	YY(1)...... 0.000
XX(2)...... 99.000	YY(2)...... 30.500
XX(3)...... 99.000	YY(3)......-30.500
XX(4)......154.000	YY(4)......107.000
XX(5)......154.000	YY(5)......-107.000

Initial values for NF, NV, I, MOOD, DELL, COW, and MOO were set up as in Table 4.

TABLE 4

Initial values for the program control variables

NF........5	MOOD........0
NV........5	DELL......2.7
I.........0	COW.......0.0
NI........0	MOO.........0

---

7. Real parts for the poles in the L.H.P. are given plus signs in order to simplify the input data. The program is set up in such a manner that this causes no problem.

An arbitrarily large number is chosen to initialize the value for REFER:

REFER..........1715.966

When the above input data has been punched on cards according to the relevant FORMAT statements, the program is compiled. The data cards from tables 2, 3, and 4 are read in along with REFER and the computer is started.

Normally, all sense switches are left OFF and the computer proceeds from statement 410 to statement 21, initializing the various control variables as follows.

```
      MOD = MOOD  =  0
      M = NI + 1 = 0+1 = 1
      N = I = 0
      NN = NI = 0
   30 NNE = NN = 0
   32 NE =  N = 0
   35 NSFP = NE = 0
      NSVP = NNE = 0
      DEL = DELL = 2.7
  250 K =  1
   21 F =  K  = 1
```

Statement no. 21 actually begins the problem solving phase of the program. This will become more evident with the consideration of a few more steps:

```
   22 N = N + 1  =  0 + 1 = 1
      NSFP = NSFP + 1 = 0 + 1=1
   25 FEE  =  FEE + ATANF((Y(N) -F)/X(N))
```

or

```
   25 FEE  =  0  +  ATANF(0.000 - 1)/(100.000)
```

which is

-0.0099996666 radian.

The situation existing in the computer as statement 25 is executed is shown in Fig. 6 below. Only the relevant pole X(1), Y(1) is shown.

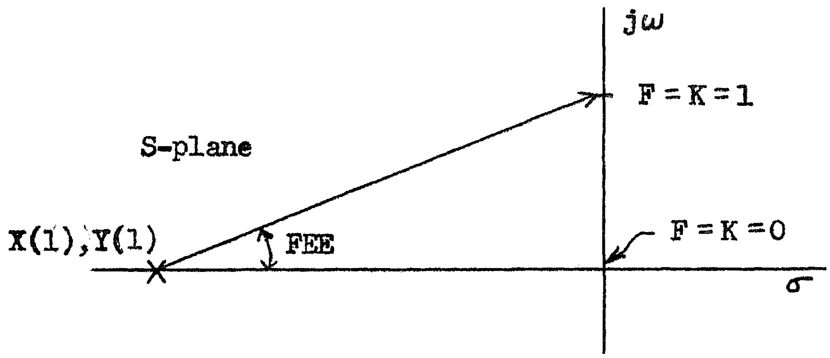


Fig. 6. Graphical representation of statement n. 25 with the computer executing this statement at the first pole for frequency equal to one.

Note that the angle FEE is made to come out as a negative quantity by subtracting the frequency 1 from the Y value of the pole. This is consistent with reality, as the phase contributed by a pole in the L.H.P. is negative for frequencies above the imaginary part of the pole.

After computing FEE, the machine proceeds to the next pole X(2), Y(2) by the following steps:

```
22 N = N + 1 = 1 + 1 = 2
   NSFP = NSFP+1 = 2
25 FEE = FEE + ATANF((Y(N) - F)/X(N))
```

or

```
   FEE = -.099996 + ATANF(58.779 - 1)/(80.902)
```

which is

+0.61018317 radian.

This process continues until FEE is summed for all of the fixed poles at the frequency F = K = 1. Then the phase angle contributed by all of the poles at frequency 1 is stored as:

```
24 FE(K) = FEE
```

or

FE(1) = -0.032360900 radian.

next the phase angle to the movable poles is calculated, using a method similar to that for the fixed poles. This process is contained in statements 23 to 13 inclusive and will not be explained in detail.

Statement 14 is executed only if there are no fixed poles. Thus the procedure passes on to statement 15 where the total phase angle to all of the poles - fixed and movable - is stored in ANG(1) as:

```
15 ANG(K) = FE(K) + FEEE
```

or

```
   ANG(1) = FE(1) + FEEE
```

and

```
   ANG(1) =            -0.069569700      radian.
```

The variables controlling the calculation of phase angle are now reinitialized so that the computation of these angles can be carried out for frequency F = K = 2.

```
 16 FEE  =  0.
    FEEE =  0.
    N = I =  0
    NN = NI =  0
    NSFP  =  NE  =  0
    NSVP  =  NNE = 0
998 ANGL  =  ANG(1) = -0.069569700 radian.
```

Statements 999 to 104 - 2, inclusive, control the storage of output data consisting of the normalized frequencies of maximum positive and negative phase error and the values, in radians, for these phase errors.

Statement 63 increments frequency to the next value as:

```
63 K = K + 1
```

or

```
K = 1 + 1 = 2
GO TO 21
```

The computer returns to statement 21 and follows the procedure outlined above for frequency F = K = 2 instead of F = K = 1. This process continues for frequencies 3, 4, 5,....100. When the machine reaches frequency 100, it will have computed the entire phase curve[8] for all of the given poles at 100 points along the frequency axis. Output data is then punched in accordance with statements 64 to 997, inclusive, as tabulated below:

TABLE 5

The First Set of Output Data Punched by the Computer

INDEX.....1	YY(1).... 0.000
POSER.....0.02123 radian	YY(2).... 30.500
KOSFQ.....56	YY(3).... -30.500
ERNEG.....0.1750 radian	YY(4).... 107.000
NEGFQ.....100	YY(5)....-107.000
XX(1).....100.000	
XX(2)..... 99.000	
XX(3)..... 99.000	
XX(4).....154.000	
XX(5).....154.000	

The actual output data as punched by the computer for four complete pole movement cycles using the data from tables 2, 3, and 4 with REFER of page 14 appears in the appendix on pages 19 through 34. Note how the first four lines of the output data correspond to table 5 above. Now examine the next four lines of the output data, observing that pole XX(1) has been moved 2.7 normalized units to the left along the real axis. How this was accomplished will now be explained.

8. That portion of curve (A) of Fig. 4 to the right of the mid-band frequency. By symmetry, the left hand portion is the same.

After punching the output data appearing above, the computer arrives at statement 997 + 1. In this statement, ERFNC, the weighted phase error area function, is compared with REFER, which is the arbitrarily large phase error area function read in the input data. Since ERFNC is less than REFER, the computer proceeds to statement 333.

```
333 KLUNK = KLUNK + 1 = 0 + 1 = 1
    GO TO 252
```

Statement 252 replaces the old REFER, 1715.966, with the just calculated value for ERFNC, 83.811. When a pole has been moved and a new ERFNC calculated, it will be compared with this new value for REFER, 83.811, in order to ascertain whether the pole movement has made the phase error better or worse.

The series of arithmetic statements beginning with ERRA = ERR(5) and ending with ERRU = ERR(100) stores twenty values of phase error, in radians, for later output data. Statements 275 through 255 - 1 reset ERFNC, POSER, ERNEG, KOSFQ, and NEGFQ so that these may be recalculated for the next pole configuration.

Pole XX(1), YY(1) is now moved 2.7 units to the left by statement 255 as follows:

```
255 GO TO(253,260,280,270,290,261,262,266,265), M
```

Since M = 1, the computer goes to statement 253 and executes it as below:

```
253  XX(1) = XX(1) + DEL
```

or

```
XX(1) = 100.000 + 2.700 = 102.700
GO TO 10
```

Pole XX(1) is now located at 102.700 and the computer has returned to statement 10 to begin a new cycle of calculations. This new cycle determines the output data appearing on lines five through eight in the output data printout on pageA19 of the appendix.

By examining the output data, the progress of pole XX(1), YY(1) may be determined. Note that the pole continues to move in steps of 2.7 units until a point is reached where the relative magnitudes of ERFNC and REFER change. The pole continues to move to the left as long as ERFNC continues to be less than REFER. When a point is reached where ERFNC is calculated to be greater then REFER (line 8 on pageA19) the pole would either have been moved the wrong way initially or moved through a point of minimum delay error. In this case, the initial movement of the pole was in the wrong direction, since the computer was "fooled" by the initial read in value for REFER. [9]

The motion of the pole is now reversed; i.e., it is now moved to the right toward the point of minimum delay error as follows:

```
251 IF(KLUNK) 258, 258, 259
```

9. Negligible machine time (in comparison to the total) is lost by this process. The writer once calculated REFER to two significant figures using a graphical process and a slide rule; this took forty hours. The machine used by the author(an IBM 1620) - quite a slow computer - will calculate refer for ten poles in about forty seconds.

Since KLUNK = 1,

259 MOD = MOD + 1

or

MOD = 0 + 1 = 1

and since MOD = 3,

249 DEL = -DEL/3.

or

DEL = -2.7/3. = -0.9

With DEL now equal to -0.9, the pole is moved to the right in successive steps of 0.9 units until the point of minimum delay error is again passed. DEL is then divided by three and its sign changed, and examination of the output data (appendix page A19) will show that the pole is now moved to the left in steps of 0.3 units until the minimum delay error point is passed for the third time.

In order to return pole XX(1) to its optimum position, it is moved 0.3 units to the right and then left at this point which gives minimum delay error. (The minimum value for ERFNC is given in the output data as 71.627.)

The next pole - actually the conjugate pair XX(2), XX(3) - is moved 2.7 units to the left, beginning the system of movements that will soon locate this pair at the X coordinate giving minimum delay error. The process of pole movements continues until all of the poles have been moved, with single poles being moved in the X direction only and conjugate pairs being moved in both the X and Y directions. All of the pole movements are summarized in table 6 on the next page.

TABLE 6

Summary of Pole Movement Directions for 5 Movable Poles

pole	movements
XX(1), YY(1)	in X (real) direction
XX(2), YY(2) XX(3), YY(3) XX(4), YY(4) XX(5), YY(5)	in X and Y (imaginary) direction as a conjugate pair

A study of the output data from the beginning (appendix p.A19) to the end (appendix p.A34) will reveal the pole movements summarized above.

Note that in the output data when the movement of a pole has been completed, three extra lines appear. Examine line 57 on page A20 of the appendix. The INDEX (actually INDIX) with a value of 13 states that it took thirteen pole movement steps to place the pole XX(1) in a position to give minimum ERFNC. Count up eight lines and note that the same number (now INDEX) appears at the start of line 49. At INDEX = 13, the pole has been located at the optimum position, four lines later the computer has determined that the point of minimum delay error has been passed, and seven lines later (line 61) the pole XX(1) has been relocated at its optimum position and the next pole movement (XX(2), XX(3)) has been executed.

The three extra lines of data appearing at each optimum pole position give the phase errors, in radians, at frequencies of 5, 10, 15,...... 100 normalized frequency units for the pole position given by the number, INDIX, punched at the start of the first of the three lines.

Sometimes one or two of the phase errors punched at an optimum pole position will correspond to POSER or ERNEG. Since ERNEG, 1.871E-01 radians, occurs at frequency 100, this value is also punched as the last entry on line 49.

When the computer has completed the entire cycle of pole movements for the first time, it arrives at statement 300 in the program and executes:

```
300   M = NI + 1
```

or

```
      M = 0 + 1 = 1
```

It then prints, on the typewriter, statement no. 77:

X-Y POLE SHIFT CYCLE COMPLETE

This tells the programmer that the machine is now going to reiterate the entire pole movement process. Execution of the program continues:

```
COW = COW + 1. = 0. + 1. = 1.0
```

and

```
  5   MOO = MOO + 1 = 0 + 1 = 1
301   DELL = DELL/3.0 = 2.7/3.0 = 0.9
      DEL = DELL = 0.9
      MOD = MOOD = 0
      GO TO 275
275   ERFNC = 0.
      POSER = 0.
      ERNEG = 0.
      KOSFQ = 0
      NEGFQ = 0

255   GO TO(253,260,280,270,290,261,262,266,265), M
```

Since M = 1, the machine proceeds to statement 253, as shown on the next page.

$$253 \; XX(1) = XX(1) + DEL$$

or

$$XX(1) = 97.600 + 0.9 = 98.500$$

The entire cycle of pole movements thus begins anew with DEL starting out as 0.9 instead of 2.7. This will give a finer resolution in locating the optimum pole positions.

On the third cycle, DEL begins with a value of 0.3, and on the fourth, or final cycle, DEL begins with a value of 0.1. On the third and fourth cycles, the number of pole movement reversals decreases, with a corresponding reduction in the number of times the variable DEL is changed. A final solution is approaching and machine time will be saved if the number of back and forth pole movements is decreased. The relative values of COW and MOOD are the controlling factors in the number of back and forth movements of the poles as the cycles progress; tables 7 and 8 show some possibilities.[10]

TABLE 7

Number of changes in the variable DEL, including that giving the final pole positioning, which occur for different values of COW with MOOD equal to zero.

COW	1st cycle	2nd cycle	3rd cycle	4th cycle
-2.0	4	4	4	4
-1.0	4	4	4	3
0.0	4	4	3	2
1.0	4	3	2	1

Line three of table 7 shows the pole movements executed by the program under discussion. As another example, consider the table on the following page, with MOOD set equal to + 1 instead of 0.

10. If the initial movement of a pole is incorrect, one more change in the variable DEL than the number indicated in the table will occur.

TABLE 8

Number of changes for variable DEL, including final positioning, which occur for different values of COW with MOOD equal to + 1.

COW	1st cycle	2nd cycle	3rd cycle	4th cycle
-2.0	3	3	3	2
-1.0	3	3	2	1
0.0	3	2	1	-
1.0	2	1	-	-

The programs of table 8 would take little machine time and would be useful in obtaining an approximate solution. Note that less than four movement cycles are possible. For line three of table 8, MOO will have to be initialized at one rather than zero to prevent a "hang up" on the nonexistent fourth cycle; similarly for line four, MOO will have to be initialized at two.

Returning to the program being discussed, table 9 below summarizes the actual pole movement steps which happen during the four complete pole movement cycles. Every single pole will have experienced each of these movements in the X direction, while every conjugate pair will have experienced each of these movements in both the X and Y directions.

TABLE 9

A Summary of the Pole Movement Increments for the Program Under Discussion

1st cycle	2.7, -0.9, 0.3, -0.3
2nd cycle	0.9, -0.3, 0.1, -0.1
3rd cycle	0.3, -0.1, 0.1
4th cycle	0.1, -0.1

Examination of the output data contained in the appendix will confirm the pole movement cycles outlined in table 9.

MOO is the variable which causes the execution of the program to cease. When MOO reaches the value four in statement 5 + 1, four complete pole movement cycles would have been completed. The following steps are then undertaken:

PRINT 107

and statement 107 is typed as:

FINAL X-Y POLE CYCLE COMPLETE. NEW DATA NEEDED

continuing,

PUNCH 108, ANGL

and ANGL is punched as

-69.830110E-03 (radians)

Evaluating the Result of the Computer Program

The programmer must then decide if the four pole movement cycles gave sufficient delay equalization. Two criteria exist which are used to ascertain the usefulness of the solution. The first involves the examination of ERFNC. If the value of ERFNC is observed to be rapidly decreasing at the end of the output data, then the optimum delay error point has not been reached and another set of pole movement cycles will be required.

To initiate a new set of pole movement cycles requires only the re-use of the final cards from the output data which give the last optimum pole locations; these are lines 820 and 821 on page A34 of the appendix.[11] The last value of REFER may be used, or the arbitrary large value used earlier may be re-used. The same card originally used to initialize NF, NV, I, NI, MOOD, DELL, COW, and MOO may also be re-used, but a new one is generally punched. In most cases, it is better to start a second complete run with a reduced initial value[12] of DELL; i.e., a value of 1.8 or 1.2 may be used instead of the original value of 2.7.[13] Below are summarized the data which might be read in for the next complete run of four cycles:

TABLE 9

Initial Data to Start a New Four Cycle Pole Movement

XX(1)	94.700	NF	5
XX(2)	99.000	NV	5
XX(3)	99.000	I	0
XX(4)	158.000	NI	0
XX(5)	158.000	MOOD	0
YY(1)	0.000	DELL	1.8
YY(2)	30.300	COW	0.0
YY(3)	-30.300	MOO	0
YY(4)	105.600		
YY(5)	-105.600		

The second criterion for evaluating the result of the computer solution involves the determining of the absolute phase errors. If ERFNC is found to be nearly static in the output data as pole movements are executed, then the poles are in their optimum positions and further computation is not necessary. By multiplying ANGL (the last line of

11. Note that here REFER is static and a new run is not necessary.

12. Note the violence done to REFER by using the large value for initial DELL of 2.7 here. The pole position of tables 2 and 3 was nearly optimum.

13. Making DELL divisible by three makes the pole movement reversals easy to follow in the output data.

output data, page A34 of the appendix) by 5, 10, 15.....100 and comparing the results with the phase errors printed on line 827 to 829 of the output data (page A34 of the appendix), the magnitude of the phase or delay error for the pole constellation may be evaluated, as will now be shown:

ERR(35) is determined from the output data to be

1.057E-03 radians

and ANGL is

-69.830110E-03 radians

and

(ANGL)(35) = -2.4440 radians.

Thus the phase error is 0.001057 radians in -2.4440 radians. Expressed as a per cent, the result is

phase error = 0.0433 %, leading.

Approximate time delay error in per cent may be established as follows:

ANGL = radians of phase shift at F = K = 1

therefore

$$\text{midband time delay} = \frac{\text{phase shift}}{\text{frequency 0 to 1}} = \frac{\text{ANGL}}{1}$$

which evaluates as

0.069830110 seconds.

Delay error will be indicated by the departures which exist along the passband from the value of this midband time delay. The value of the time delay at $F = K = 35$ is determined approximately as:

$$\text{TIME DELAY} = \frac{\dfrac{\text{PHASE SHIFT IN FREQUENCY 30 TO 35}}{5} + \dfrac{\text{PHASE SHIFT IN FREQUENCY 35 TO 40}}{5}}{2},$$

or

$$\text{TIME DELAY} = \frac{\dfrac{0.346723}{5} + \dfrac{0.347055}{5}}{2},$$

which gives

0.069377 seconds @ frequency 35.

Thus the delay error with respect to the mid-band delay is given by:

$$\text{DELAY ERROR, \%} = \frac{\text{MID-BAND DELAY} - \text{DELAY AT 35}}{\text{MID-BAND DELAY}}$$

or

$$\text{DELAY ERROR, \%} = \frac{0.069830 - 0.069377}{0.069830} = 0.648 \text{ \%}.$$

A more accurate result, if needed, may be obtained by calling from the computer memory the final value of the entire array ERR(K). Resolution of ERR(K) to frequencies only one unit apart would then be possible, as opposed to the resolution of the punched data, which gives phase errors for frequencies five units apart. The equation for delay error given above can then be used to determine the delay error, as before.

Some Further Details

The possibility may arise that the delay error is excessive when the optimum pole constellation is reached, as indicated by no further reduction in ERFNC. Two possible reasons exist for the difficulty: (1) The delay error due to the fixed poles is so great that the specified number of movable poles cannot achieve delay equalization, and (2) delay equalization over too great a bandwidth is being attempted.

Resolving the difficulty involves either adding more movable poles and/or modifying the weighting of the error function. The adding of more poles is a fairly easy task, at least in principle, and needs no special explanation.

Modifying the weighting of the error function involves the adjustment of the two quantities CONST and FB. This is achieved by starting the program going with SENSE SWITCH ONE turned ON. The machine will then type:

INSERT CONST, FB

Using the typewriter, new values of CONST and FB are read into the program. Generally CONST will be left at the value 1.0, but to attach less importance to delay errors far removed from the mid-band frequency, FB is made smaller; it may be made less than 100, so that the computer will deliberately accentuate the delay error at the band edges in order to achieve less delay error near the mid-band frequency.

Generally, small values of FB and CONST will give a delay error characteristic tending toward an "equal ripple" condition, while large values for FB and CONST will produce a delay error characteristic tending toward a "maximally flat" condition.

Conclusion

The explanation of the computer program given here is by no means complete. Indeed, a full exposition would require a book and is beyond the scope of this paper. However, given a through understanding of the operation of the program for the given example above, the reader will, with further study of the program, its flow chart, and tables one through nine, come to a full understanding of its operation. To further assist the reader in comprehending the operation of the program, the complete set of input data used in computing all of the pole locations given in the appendix is given along with the relevant pole locations.

APPLICATION OF THE RIMO FILTER TO THE FM IF AMPLIFIER

The real usefulness of the Rimo filter lies in its application to FM transmission. Ideally, FM signals are sensitive to phase information only, and it is this characteristic that makes Rimo filters useful for FM transmission. These filters have nominally linear phase response and moderately rounded amplitude response within their passbands, and high attenuation outside their passbands. If an FM signal is applied to a Rimo filter, it will pass through with its important phase information negligibly distorted. The moderate amplitude distortion which results would be easily handled by a good limiter, while the high selectivity will effectively suppress alternate channel signals.

Full realization of the potential inherent in the Rimo filter concept utilized in an FM IF amplifier design requires some care in the layout of the system. Poles of a Rimo filter are chosen on the basis of required selectivity and allowable circuit complexity. Two experimental FM receivers have been built using the Rimo filter concept, the first being a "state of the art" tuner and the second being a table radio. Both use identical 5-pole Butterworth filters with five equalizer poles, with the equalizer poles being realized in a different manner in each.

A functional block diagram of the tuner is shown in Fig. 7, and that of the radio is shown in Fig. 8 on the next page.

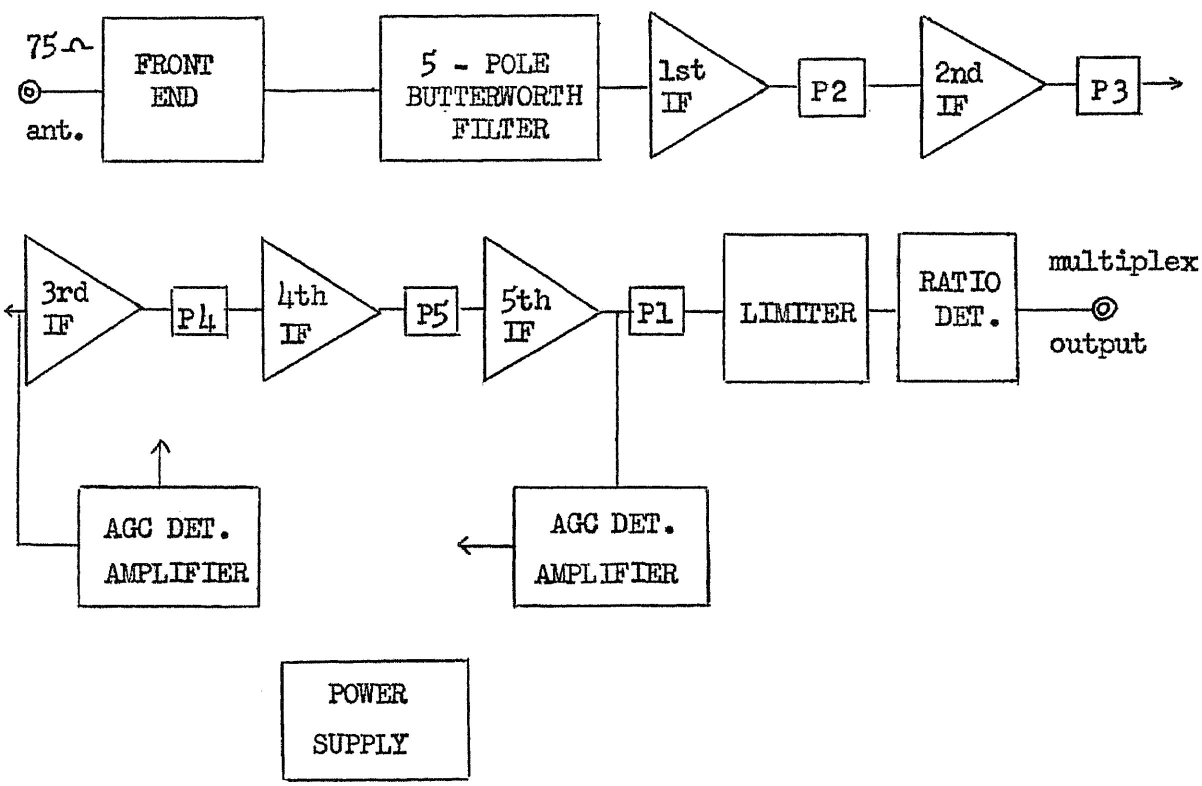


Fig. 7. Functional block diagram for the tuner. The five interstage networks are the five equalizer poles (P1 through P5).

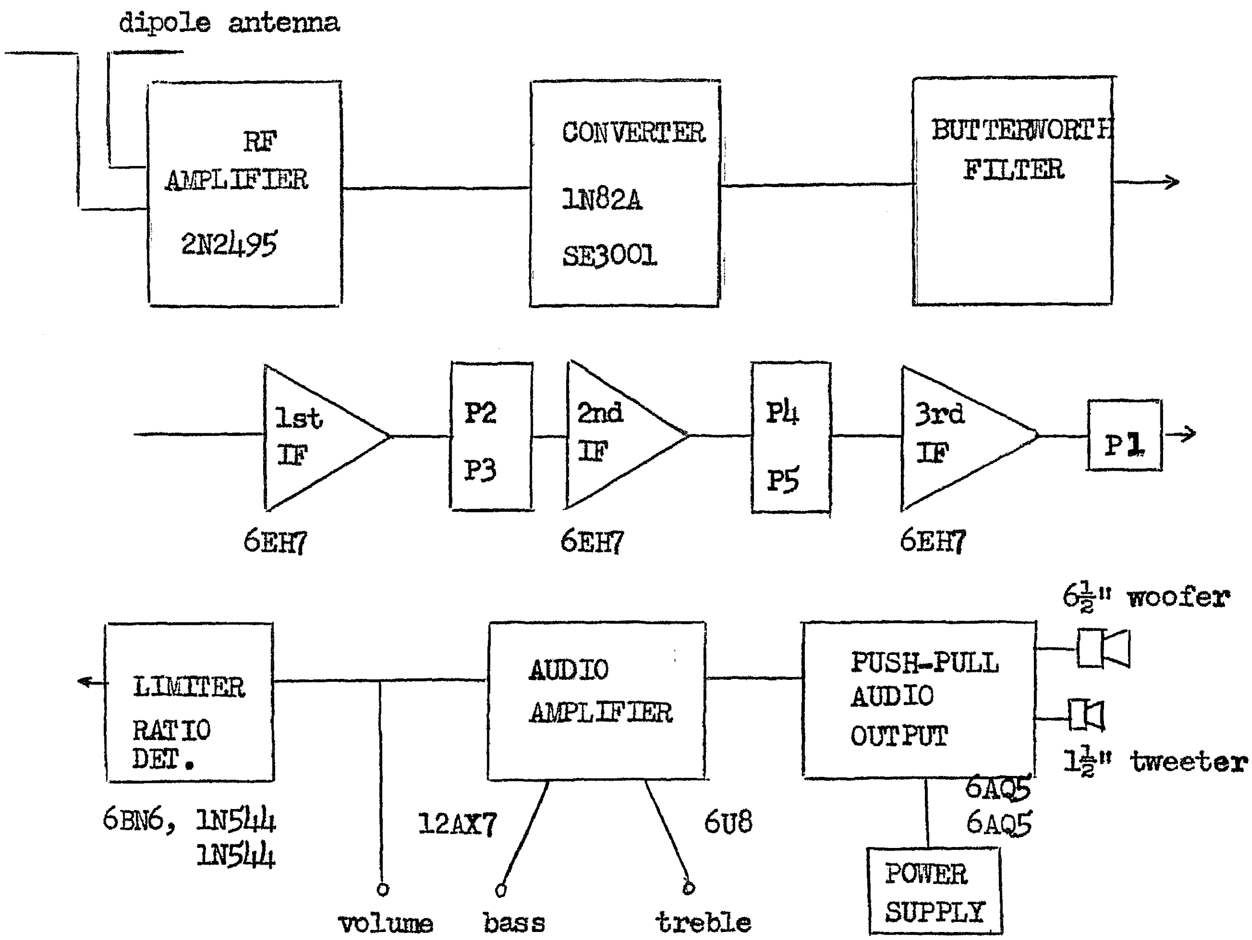


Fig. 8. Functional block diagram for the radio. The equalizer poles are realized as two double-tuned and one single tuned interstage.

Note that in realizing the Rimo filter, the poles were split. The Butterworth portion, which comprises much of the selectivity, is a lumped passive filter following the mixer. The less selective equalizer poles are distributed as interstage networks between the IF amplifier stages. Some of the care in realizing the Rimo filter - amplifier system should now be evident. Overloading of the IF amplifier by strong alternate channel signals is reduced to a minimum by placing the selective Butterworth poles in a filter before the first IF amplifier. The less critical low-Q equalizer poles are placed in the IF amplifier beginning with the higher Q poles and ending with the lower Q poles. The single center pole is placed between the last IF stage and the limiter. Reserving the center pole for the final (output) position in a tuned amplifier is common practice, as it gives maximum output capability [14] in the center of the bandpass where it is generally most needed.

An FM tuner must accept signals which vary at the antenna input from levels of less than a microvolt to over a volt, and with this great variation still produce an output which is as free of noise and distortion as possible. Since the information contained in an FM signal is determined by phase only and not by amplitude, it might seem possible in an FM receiver to use a low-noise RF amplifier followed by the mixer, IF amplifier, and detector, and run the whole receiver at full gain at all times, using no AGC. However, under these conditions, when a relatively weak desired channel is being received among several strong near-by channels, all of the signals could arrive limited to the same amplitude level at the detector, causing cross-talk and distortion.

A better situation would result if the receiver were to have a highly selective, closely gain controlled IF amplifier preceding the limiter, and allow the limiter to smooth only the IF response in the desired channel. Off channel signals would then enter the limiter and detector at a lower level than the desired signal determined by the IF selectivity. Somewhat elaborate circuitry is used in the tuner to achieve a very constant input amplitude to the limiter and detector. The radio uses a standard AGC circuit which follows common design practice.

14. Tuned amplifiers generally have an odd number of poles to allow the placing of the single odd pole at the output position.

The remainder of the circuitry in the tuner follows somewhat standard practice. The four-tube front end gives the required 45 db of gain before the first IF grid, with delayed AGC applied to the two RF stages. The 6BA7 mixer, although noisy, has excellent overload capability and good conversion gain. A schematic and performance characteristics of the tuner are presented in the appendix.

The table radio uses a Rimo filter in addition to otherwise orthodox circuitry. Performance data appear in the appendix.

Considerable work on both the tuner and radio remains unfinished, with neither unit in a static condition and both still undergoing constant experimentation. Among some things awaiting further study are a multiplex decoder for the tuner, and an investigation of distortion of the signal caused by imperfect limiting.

CONCLUSION

In the field of minimum-phase filters, the Rimo filter is to phase sensitive signals as the flat-amplitude approximations are to amplitude sensitive signals. Using the charts or the computer program presented in the appendix, the designer may choose the poles of a minimum-phase constant delay filter of any desired selectivity, in a manner exactly analogous to the selection of a minimum-phase flat amplitude filter of any desired selectivity.

In both the tuner and radio, the result of the application of the Rimo filter concept to the IF amplifier design has been gratifying. The performance of the tuner is nothing short of excellent, and the reception of stereo broadcasts[15] from distant stations has been of

15. An Eico model MX-99multiplex decoder is presently in use with the tuner.

consistently good quality. In many cases, these distant signals are not audible on other tuners due to their poor selectivity.

The Rimp filter concept as presented in this paper is very incomplete - indeed it is only a beginning. The Rimo filter is still in its genesis and much experimentation with the computer program will be necessary before any general conclusions can be made concerning these filters. Among the aspects in consideration for future exploration is the effect of the area weighting function on the amplitude and phase response of Rimo filters.

An important aspect to be pursued is the determination of exact solutions for maximally-flat and equal-ripple time delay filters using the computer program - if such solutions exist.

Current plans call for a continued research in Rimo filters beyond this thesis with the abovementioned ideas forming the basis for the future investigation.

REFERENCES

PARTICULAR

1. Modafferi, R. "A New Design Approach for a Low Distortion 10.7 MC IF Amplifier" Newark College of Engineering, December 1963. (Unpublished)

2. Kuo, F.F. Network Analysis and Synthesis New York: John Wiley & Sons, 1962

GENERAL

3. Tibbs, C & Johnstone, G Frequency Modulation Engineering New York: John Wiley and Sons, 1956 Second Edition, revised.

APPENDIX

PERFORMANCE DATA, BUTTERWORTH TUNER

taken from Ref. 1,

page 27.

IHFM SENSITIVITY:	Local: 2uv across 75 ohms Distant: 0.7 uv across 75 ohms
LOCAL OSCILLATOR DRIFT.	Less than 2KC after 5 minute warmup and 10% line voltage change
CAPTURE RATIO:	3 DB
TUNING RANGE:	86.5 to 110 MC
NOISE FIGURE:	distant: 2.1 DB
SPURIOUS RESPONSES:	distant: down at least 60 DB local: down at least 84 DB
INPUT VSWR:	less than 1.2:1 referred to 75 ohm input
RATIO DETECTOR BANDWIDTH:	800 KC peak to peak
AUDIO OUTPUT:	1 volt nominal at 1KC, 100% modulation
SIGNAL TO NOISE RATIO:	70 DB or greater for input 1000 uv

additional data

NUMBER OF VACUUM TUBES	12
NUMBER OF SEMICONDUCTORS	15
HARMONIC DISTORTION:	Less than 0.3% for 100% modulation, 50 CPS to 15KCPS, 1000 uv input

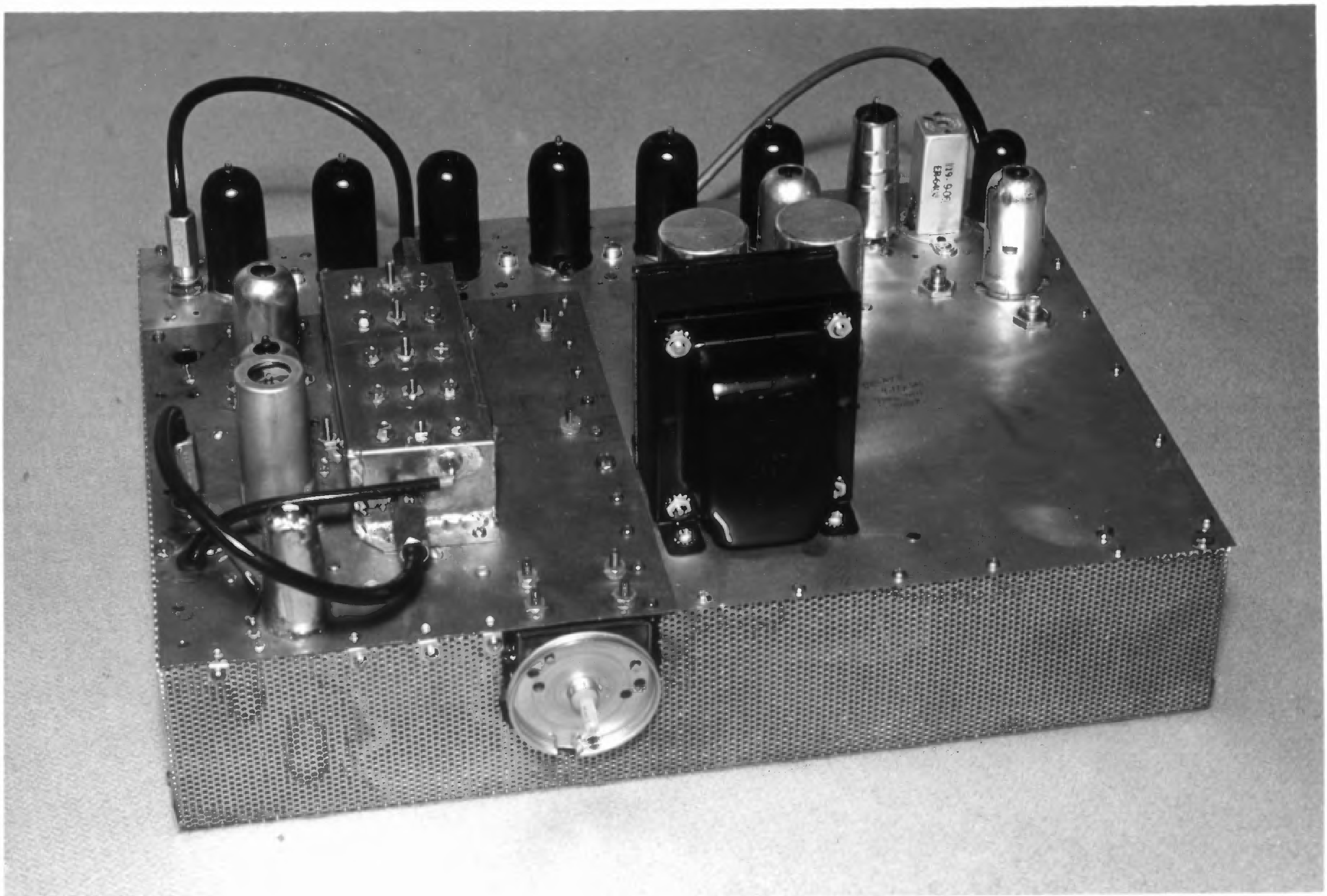
Note: A simpler version of this tuner was constructed, using 11 tubes and three semiconductors, and gave essentially the same performance as listed above. It is still in use.

PERFORMANCE DATA, RIMO FILTER TUNER

IHFM SENSITIVITY:	1.5uv across 75 ohms
LOCAL OSCILLATOR DRIFT:	Less than 2KC after 5 minute warmup and 10% line voltage change
CAPTURE RATIO:	2 DB
TUNING RANGE:	86.5 to 110 MC
NOISE FIGURE:	6 DB
SPURIOUS RESPONSES:	image and second harmonic oscillator conversion, down at least 90 DB; all other spurious down at least 100 DB
INPUT VSWR:	less than 1.2:1 referred to 75 ohms
RATIO DETECTOR BANDWIDTH:	1.5 MC peak to peak
AUDIO OUTPUT:*	2.0 volts nominal at 1KC, 100% modulation
SIGNAL TO NOISE RATIO:	70 DB or greater for input 50 uv

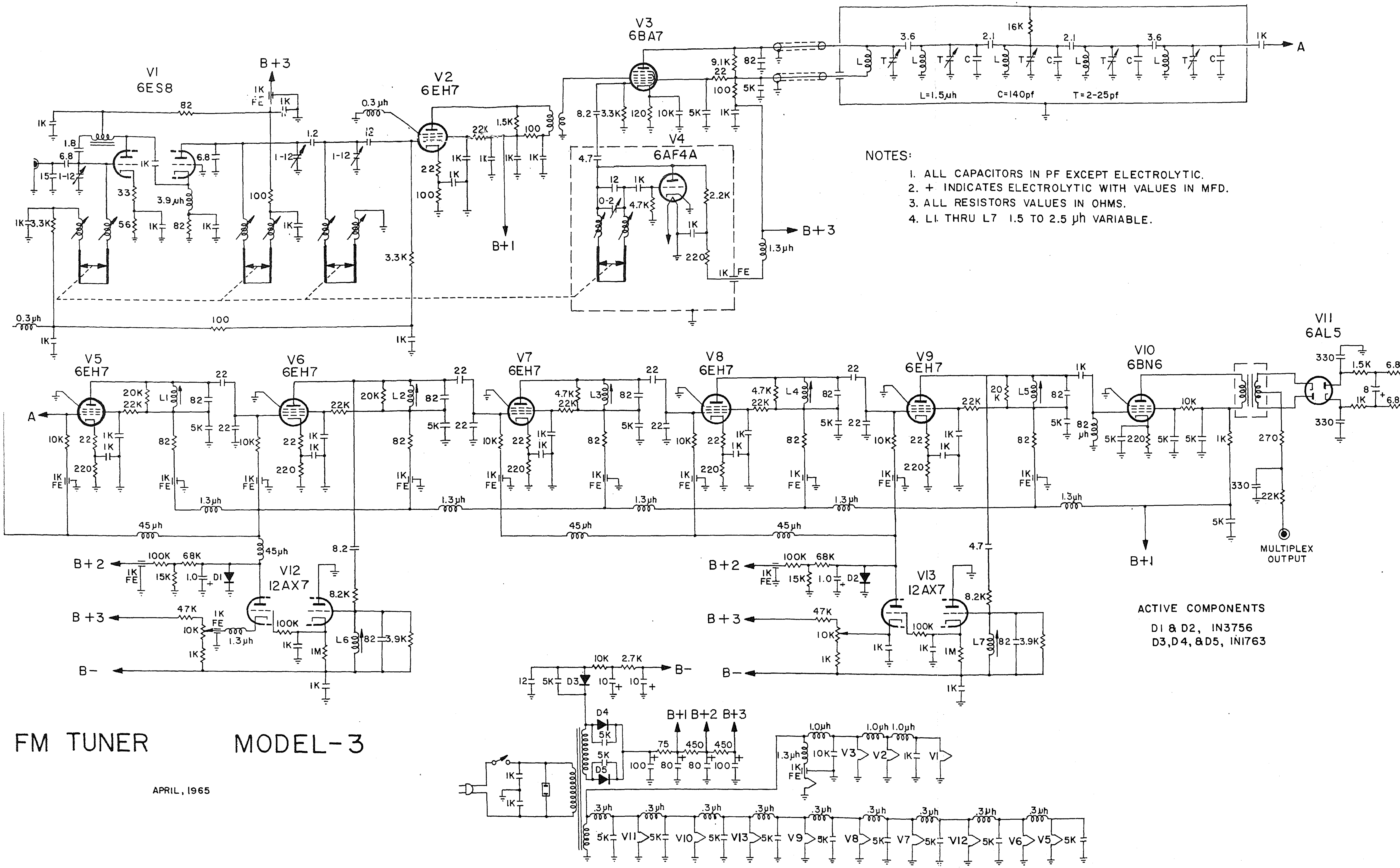
NUMBER OF VACUUM TUBES	14, less multiplex decoder
NUMBER OF SEMICONDUCTORS	5
HARMONIC DISTORTION	essentially unmeasurable in mono or stereo on available test equipment; distortion in stereo mode on frequencies not subharmonically related to 19KC is probably less than 1%
IF BANDWIDTH:	@6DB: 221 KC
	@60 DB: 594 KC
	@90 DB: 865 KC

* An audio output stage has been added to the tuner and does not appear in the schematic.



The Rimo filter tuner. The front end chassis, left front, is a carry-over from the original tuner built in 1962. The space on the right front is reserved for a cathode-ray tuning indicator similar to that now used on the Marantz model 10 tuner. An Eico MX-99 multiplex decoder is now in use with this tuner, and present plans are to keep it as its performance is entirely satisfactory.

The rectangular box on top of the front end chassis is the Butterworth filter; note the five trimmer screws. By using a cable and plug format for the filter, it may be easily disconnected and another one substituted; this facilitated experimentation in the early stages of the tuner design.



NOTES:

1. ALL CAPACITORS IN PF EXCEPT ELECTROLYTIC.
2. + INDICATES ELECTROLYTIC WITH VALUES IN MFD.
3. ALL RESISTORS VALUES IN OHMS.
4. L1 THRU L7 1.5 TO 2.5 μh VARIABLE.

ACTIVE COMPONENTS

D1 & D2, IN3756
D3, D4, & D5, IN1763

FM TUNER MODEL-3

APRIL, 1965

PERFORMANCE DATA, TABLE RADIO

IHFM SENSITIVITY:	0.5uv across 300 ohms
LOCAL OSCILLATOR DRIFT:	less than 25KC after 10 minutes warmup
CAPTURE RATIO:	6 DB, approx.
TUNING RANGE:	87 to 109 MC
NOISE FIGURE:	2.1 DB
SPURIOUS RESPONSES:	image down at least 35 DB, all other spurious down at least 40 DB
INPUT VSWR:	3:1 approx.
RATIO DETECTOR BANDWIDTH:	300 KC
EFFECTIVE AUDIO FREQUENCY RANGE	100 cycles to 15 KC
AUDIO OUTPUT	3 watts

Note: The front end in this radio has been designed to operate from a built in cabinet antenna, which dictated a design based on highest possible sensitivity. The low-noise RF amplifier now used in the radio was originally used in the old tuner of Ref. 1.

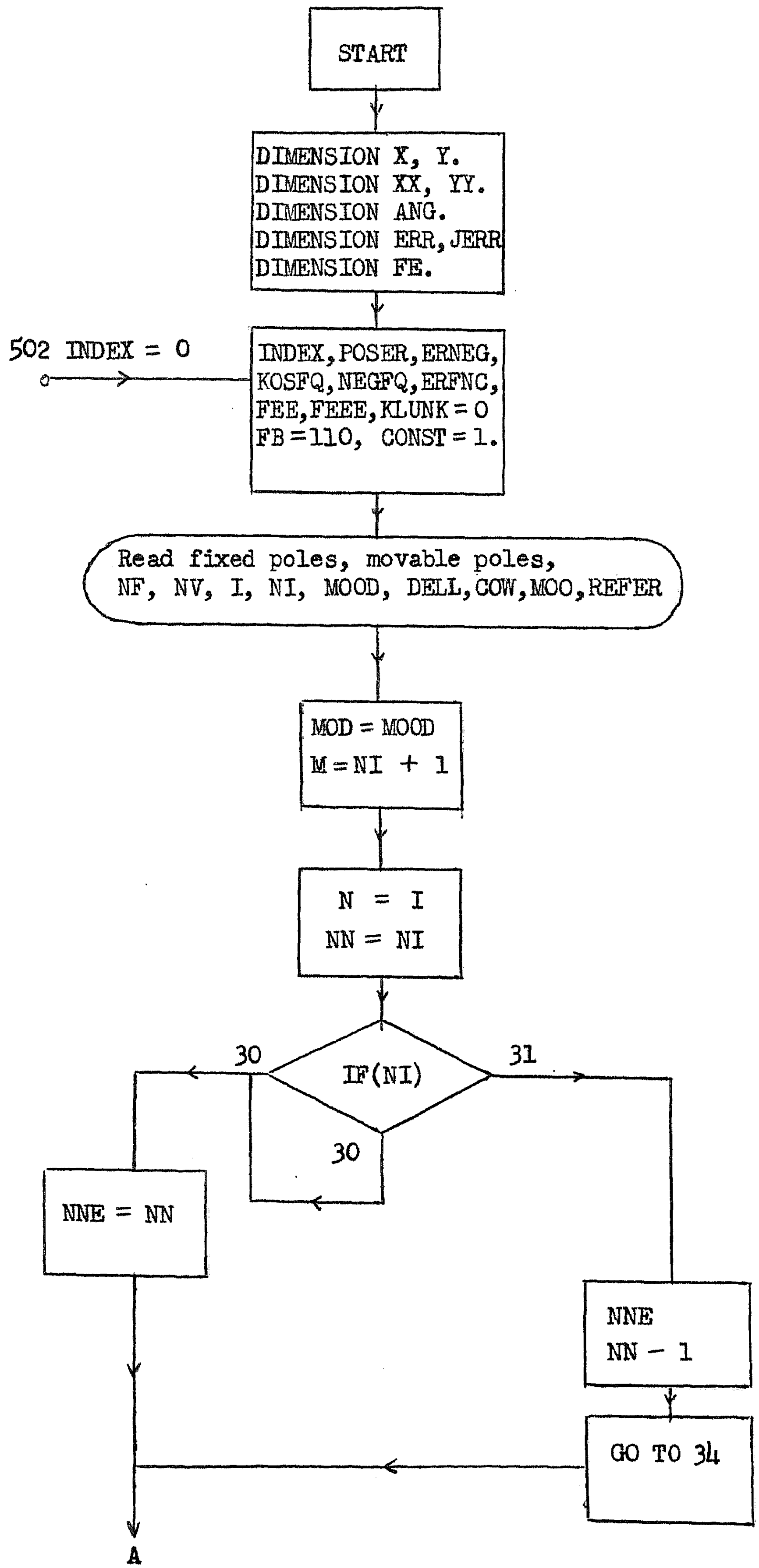
The Rimo filter radio. This experimental radio was built with the idea of incorporating a high quality circuit in a small cabinet, allowing quality FM reception anywhere within reach of a power line outlet. The very high sensitivity of the radio makes good reception possible with the built in antenna, even in weak signal areas. At Liberty, NY, most of the New York City stations were received, at a distance of more than 100 miles.

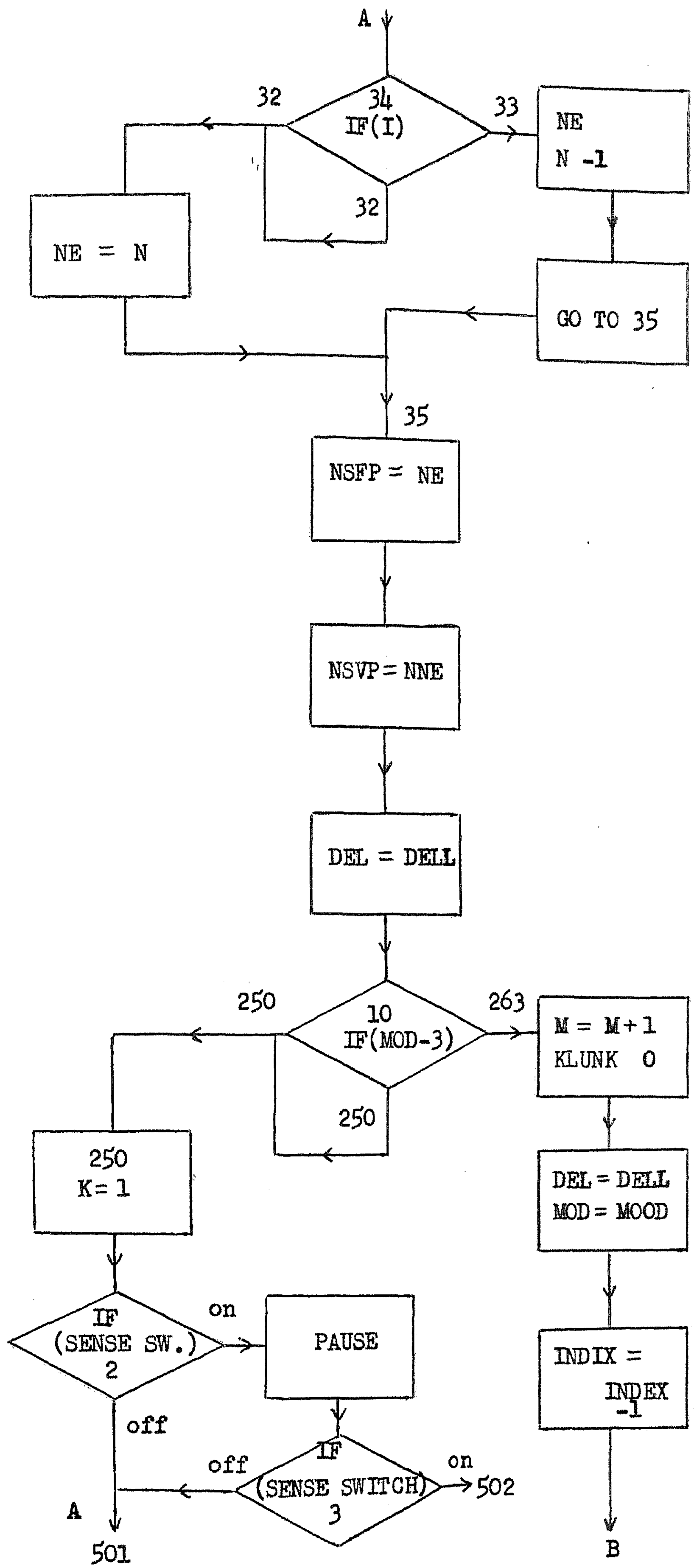
```
C   C   DELAY EQUALIZATION OF MINIMUM PHASE FILTERS
C   C   MASTERS THESIS BY RICHARD MODAFFERI ADVISOR RH ROSE.
        DIMENSION X(10),Y(10)
        DIMENSION XX(10), YY(10)
        DIMENSION ANG(100)
        DIMENSION ERR(100)
        DIMENSION JERR(100)
        DIMENSION FE(100)
502     INDEX = 0
        POSER =0.
        ERNEG=0.
        KOSFQ=0
        NEGFQ=0
        ERFNC =0.
        FB = 110.
        FEE = 0.
        FEEE = 0.
        CONST = 1.0
        KLUNK = 0
        READ 400, X(1), X(2), X(3), X(4), X(5)
        READ 400, X(6), X(7), X(8), X(9), X(10)
        READ 400, Y(1), Y(2), Y(3), Y(4), Y(5)
        READ 400, Y(6), Y(7), Y(8), Y(9), Y(10)
400     FORMAT(5F8.3)
        READ401,XX(1),XX(2),XX(3),XX(4),XX(5)
        READ401,YY(1),YY(2),YY(3),YY(4),YY(5)
        READ 401, XX(6), XX(7), XX(8), XX(9)
        READ 401,  YY(6), YY(7), YY(8), YY(9)
401     FORMAT(5F8.3)
        READ402, NF, NV, I, NI, MOOD, DELL, COW, MOO
402     FORMAT(I2,4XI2,4XI2,4XI2,4XI2,4XF4.1,2XF3.0,4XI2)
        READ 410, REFER
410     FORMAT (F8.3)
        MOD = MOOD
        M = NI+ 1
        N = I
        NN = NI
        IF(NI) 30, 30, 31
31      NNE = NN - 1
        GO TO 34
30      NNE = NN
34      IF(I) 32, 32, 33
33      NE = N - 1
        GO TO 35
32      NE = N
35      NSFP = NE
        NSVP = NNE
        DEL = DELL
10      IF (MOD - 3) 250, 263, 263
263     M = M + 1
        KLUNK = 0
```

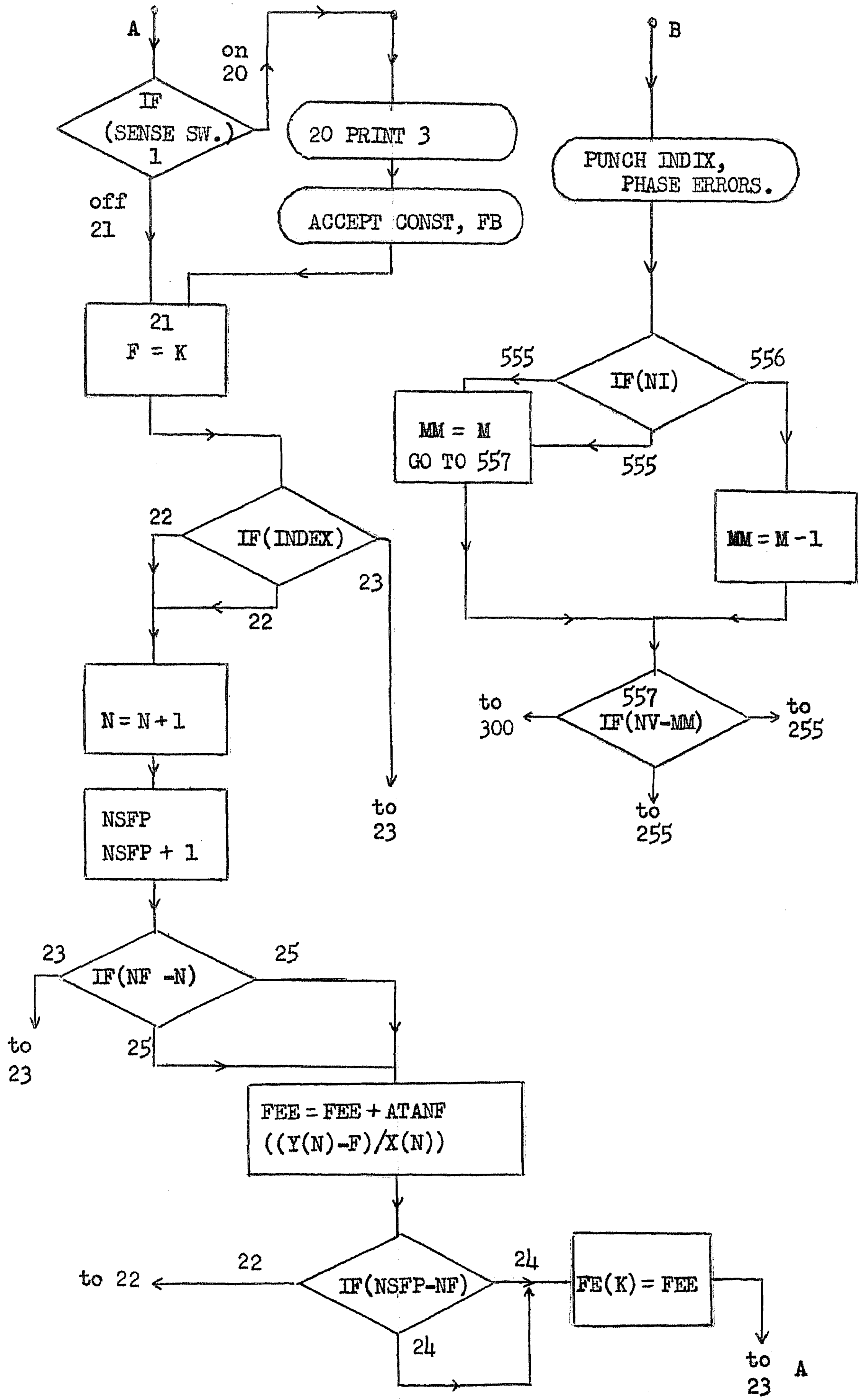
```
      DEL = DELL
      MOD = MOOD
      INDIX = INDEX - 1
      PUNCH 102, INDIX, ERRA, ERRB, ERRC, ERRD, ERRE, ERRG
102   FORMAT (I5,6E10.3)
      PUNCH 103, ERRH, ERRI, ERRJ, ERRK, ERRL, ERRM, ERRN
      PUNCH 103, ERRO, ERRP, ERRQ, ERRR, ERRS, ERRT, ERRU
103   FORMAT(7E10.3)
      IF(NI) 555, 555, 556
555   MM = M
      GO TO 557
556   MM = M - 1
557   IF(NV - MM) 300, 255, 255
250   K = 1
      IF (SENSE SWITCH 2) 500, 501
500   PAUSE
      IF (SENSE SWITCH 3) 502, 501
501   IF (SENSE SWITCH 1 ) 20,21
20    PRINT 3
3     FORMAT (17H INSERT CONST, FB)
      ACCEPT 4, CONST, FB
4     FORMAT(F5.3, F3.0)
21    F = K
      IF (INDEX) 22, 22, 23
22    N = N + 1
      NSFP = NSFP + 1
      IF (NF - N) 23, 25, 25
25    FEE = FEE + ATANF((Y(N) -F)/X(N))
      IF(NSFP - NF) 22, 24, 24
24    FE(K) = FEE
23    NN = NN + 1
      NSVP = NSVP + 1
      FEEE = FEEE + ATANF((YY(NN)-F)/XX(NN))
      IF(NSVP - NV) 23, 13, 13
13    IF (NF) 14, 14, 15
14    ANG(K) = FEEE
      GO TO 16
15    ANG(K) = FE(K) + FEEE
16    FEE = 0.
      FEEE = 0.
      N = I
      NN = NI
      NSFP = NE
      NSVP = NNE
      IF(INDEX) 998,998,999
998   ANGL = ANG(1)
999   ERR(K) =ANG(K) - ANGL*F
      DELTA = CONST * ERR(K) * (FB - F)
      DELTA = ABSF(DELTA)
      ERFNC = ERFNC + DELTA
      JERR(K) = 10000.*ERR(K)
      IF(JERR(K)) 60,62,58
58    IF (ERR(K) - POSER) 62, 62, 59
59    POSER = ERR(K)
```

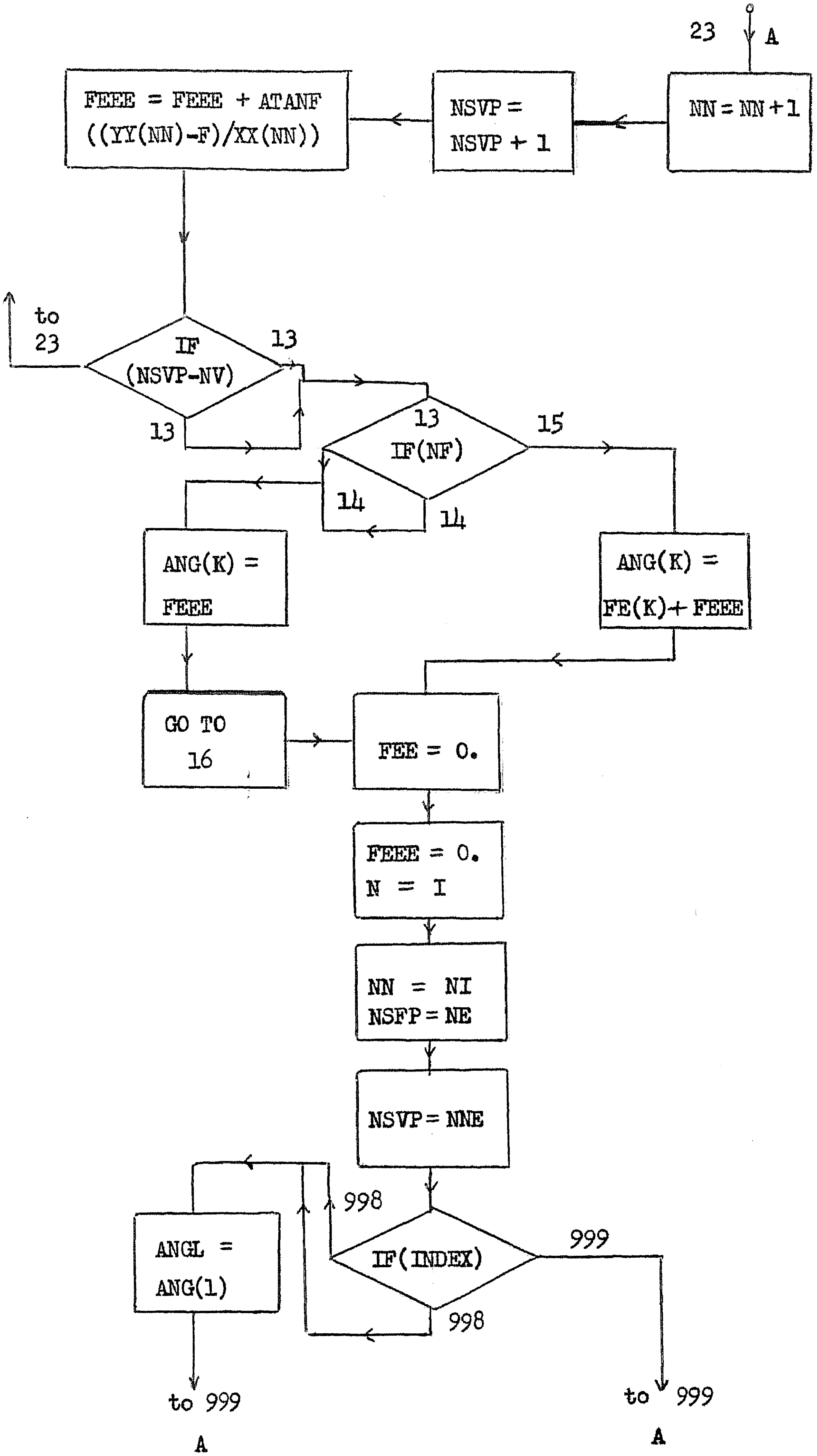
```
      KOSFQ = K
      GO TO 62
60    IF (ERNEG + ERR(K)) 61, 62, 62
61    ERNEG = -ERR(K)
      NEGFQ = K
62    IF(K-100) 63, 64, 65
65    PRINT 104
104   FORMAT(22H FREQUENCY EXCEEDS 100)
      PAUSE
      GO TO 502
63    K = K + 1
      GO TO 21
64    INDEX = INDEX + 1
      PUNCH 100, INDEX, POSER, KOSFQ, ERNEG, NEGFQ
100   FORMAT(I10,E10.3,I10,E10.3,I10)
      PUNCH 101, XX(1),XX(2),XX(3),XX(4),XX(5)
      PUNCH 101, YY(1),YY(2),YY(3),YY(4),YY(5)
101   FORMAT(5F8.3)
      IF(NV - 5) 149, 149, 150
150   PUNCH 101, XX(6), XX(7), XX(8), XX(9)
      PUNCH 101, YY(6), YY(7), YY(8), YY(9)
149   PUNCH 997, ERFNC, REFER
997   FORMAT (2F20.3)
      IF(ERFNC - REFER) 333, 333, 251
333   KLUNK = KLUNK + 1
      GO TO 252
251   IF(KLUNK) 258, 258, 259
258   DEL = -DEL
      KLUNK = KLUNK + 1
      GO TO 252
259   MOD = MOD + 1
      IF(MOD - 3) 249, 264, 264
264   DEL = -DEL
      GO TO 275
249   DEL = -DEL/3.
252   REFER = ERFNC
      ERRA = ERR(5)
      ERRB = ERR(10)
      ERRC = ERR(15)
      ERRD = ERR(20)
      ERRE = ERR(25)
      ERRG = ERR(30)
      ERRH = ERR(35)
      ERRI = ERR(40)
      ERRJ = ERR(45)
      ERRK = ERR(50)
      ERRL = ERR(55)
      ERRM = ERR(60)
      ERRN = ERR(65)
      ERRO = ERR(70)
      ERRP = ERR(75)
      ERRQ = ERR(80)
      ERRR = ERR(85)
      ERRS = ERR(90)
```

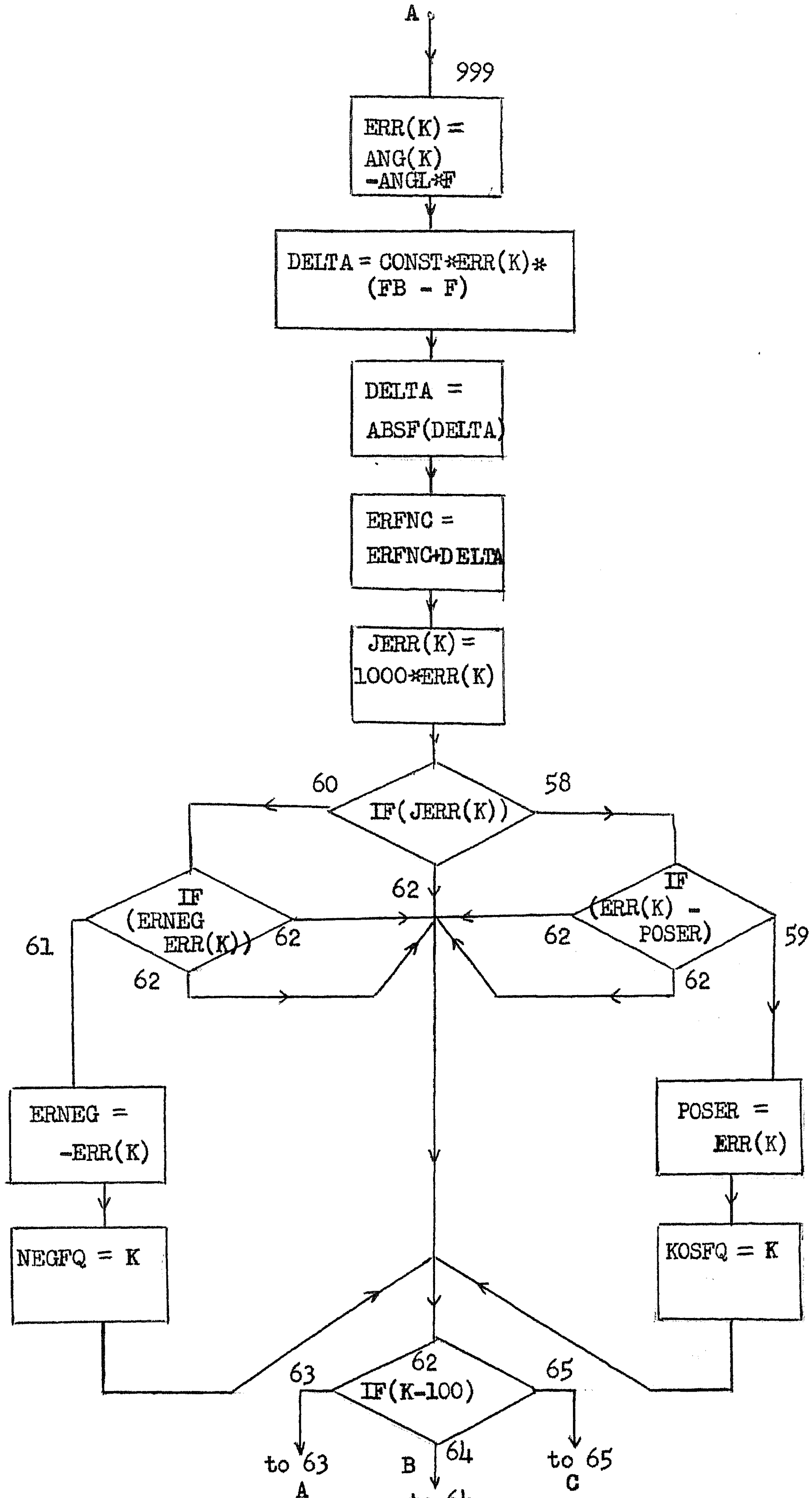
```
      ERRT = ERR(95)
      ERRU = ERR(100)
275   ERFNC = 0.
      POSER = 0.
      ERNEG = 0.
      KOSFQ = 0
      NEGFQ = 0
255   GO TO (253, 260, 280, 270, 290, 261, 262, 266, 265), M
253   XX(1) = XX(1) + DEL
      GO TO 10
260   XX(2) = XX(2) + DEL
      XX(3) = XX(3) + DEL
      GO TO 10
280   YY(2) = YY(2) + DEL
      YY(3) = YY(3) - DEL
      GO TO 10
270   XX(4) = XX(4) + DEL
      XX(5) = XX(5) + DEL
      GO TO 10
290   YY(4) = YY(4) + DEL
      YY(5) = YY(5) - DEL
      GO TO 10
261   XX(6) = XX(6) + DEL
      XX(7) = XX(7) + DEL
      GO TO 10
262   YY(6) = YY(6) + DEL
      YY(7) = YY(7) - DEL
      GO TO 10
266   XX(8) = XX(8) + DEL
      XX(9) = XX(9) + DEL
      GO TO 10
265   YY(8) = YY(8) + DEL
      YY(9) = YY(9) - DEL
      GO TO 10
300   M = NI + 1
      PRINT 77
77    FORMAT(31H X-Y POLE SHIFT CYCLE COMPLETE.)
      COW = COW + 1.
      IF (COW - 1.5) 5, 5, 6
6     MOOD = MOOD + 1
5     MOO = MOO + 1
      IF (MOO - 4) 301, 106, 106
301   DELL = DELL/3.0
      DEL = DELL
      MOD = MOOD
      GO TO 275
106   PRINT 107
107   FORMAT (47H FINAL XY POLE CYCLE COMPLETE. NEW DATA NEEDED.)
      PUNCH 108, ANGL
108   FORMAT(E14.6)
      GO TO 502
      END
```

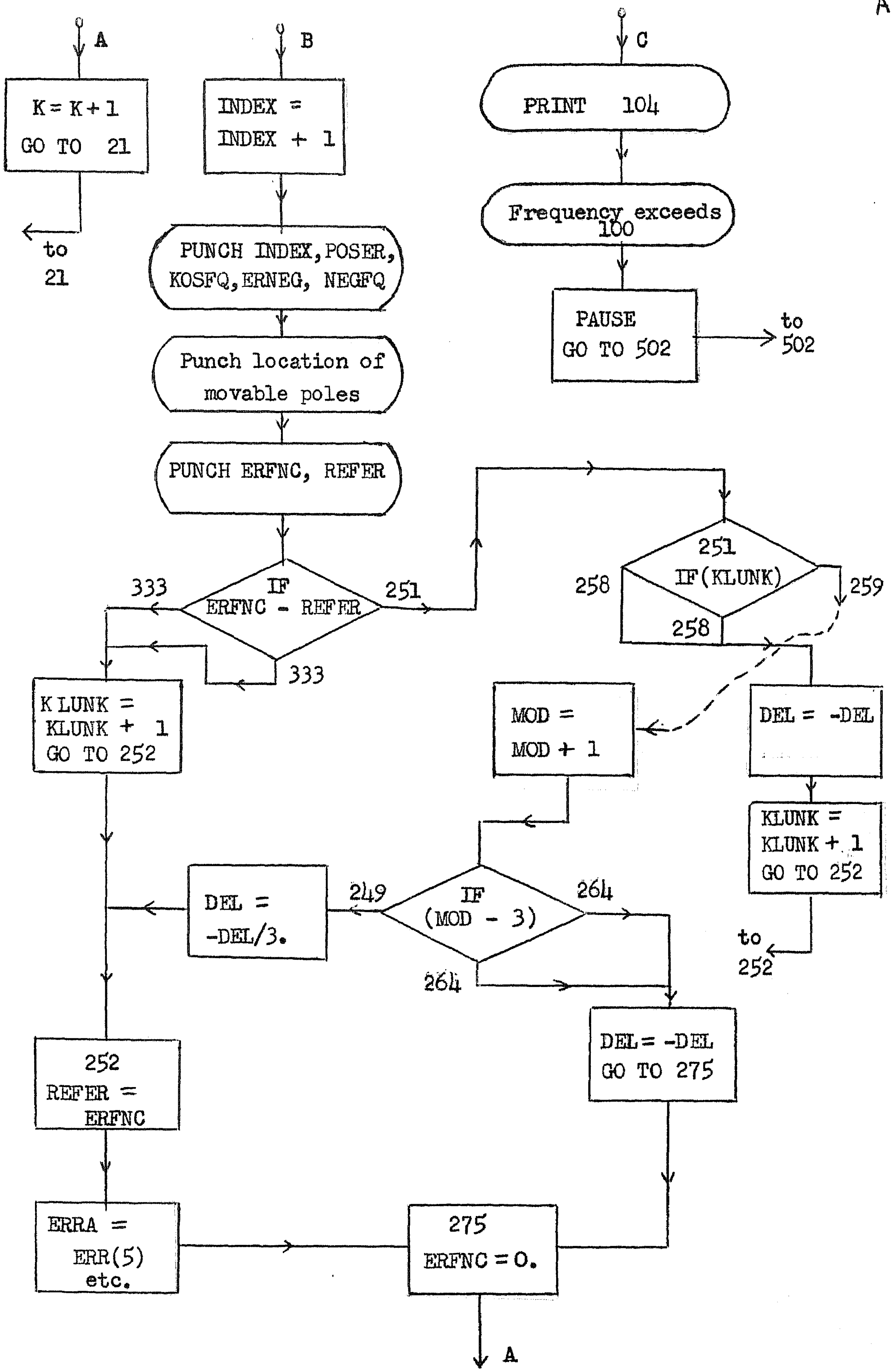

START
DIMENSION X, Y.
DIMENSION XX, YY.
DIMENSION ANG.
DIMENSION ERR, JERR
DIMENSION FE.
502 INDEX = 0
INDEX, POSER, ERNEG,
KOSFQ, NEGFQ, ERFNC,
FEE, FEEE, KLUNK = 0
FB = 110, CONST = 1.
Read fixed poles, movable poles,
NF, NV, I, NI, MOOD, DELL, COW, MOO, REFER
MOD = MOOD
M = NI + 1
N = I
NN = NI
30
IF(NI)
31
30
NNE = NN
NNE
NN − 1
GO TO 34
A

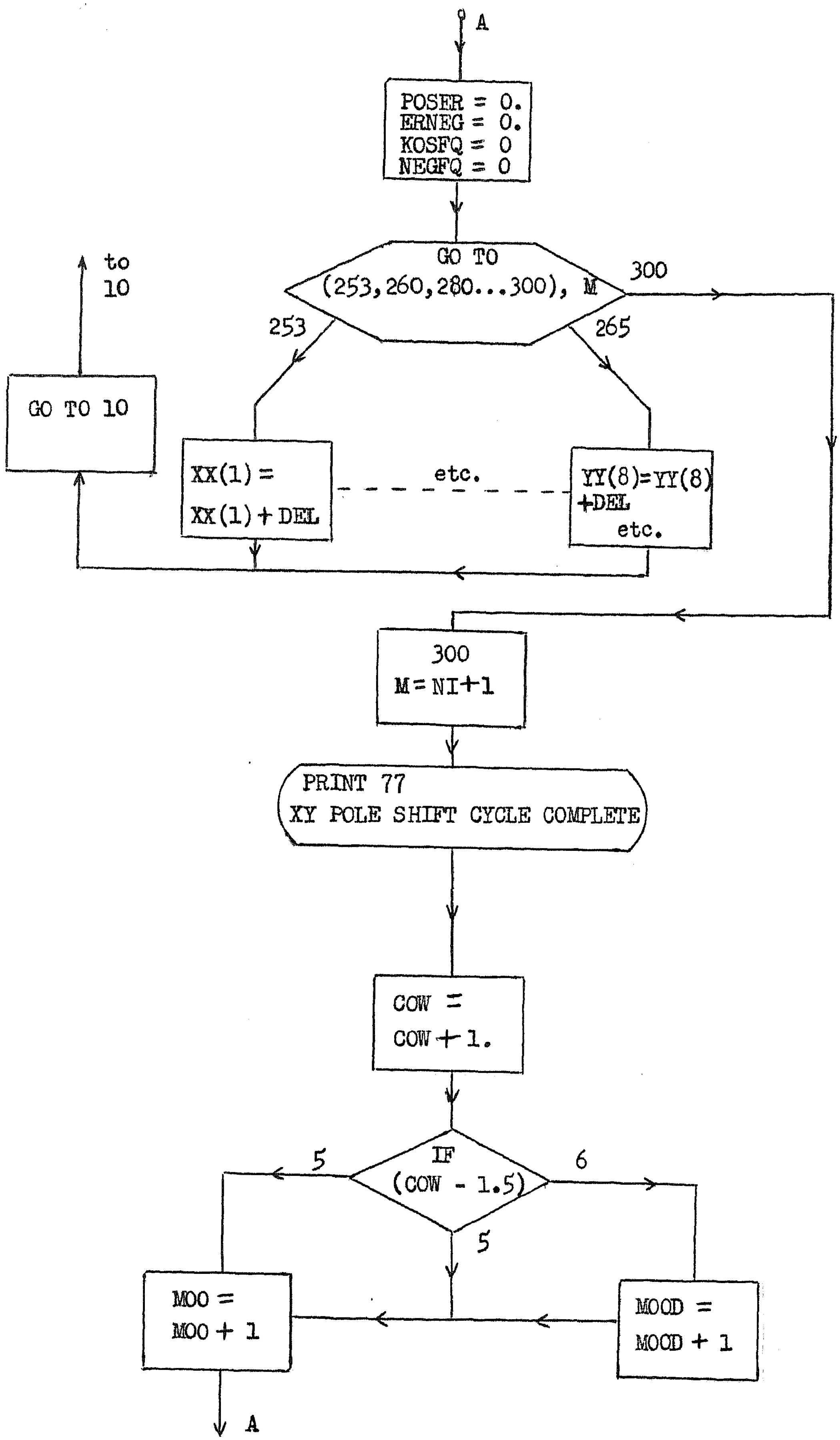

A
34
IF(I)
32
33
NE
N -1
32
NE = N
GO TO 35
35
NSFP = NE
NSVP = NNE
DEL = DELL
250
10
IF(MOD-3)
263
M = M+1
KLUNK 0
250
250
K = 1
DEL = DELL
MOD = MOOD
IF
(SENSE SW.)
2
on
PAUSE
INDIX =
INDEX
-1
off
IF
off
(SENSE SWITCH)
3
on
502
A
501
B

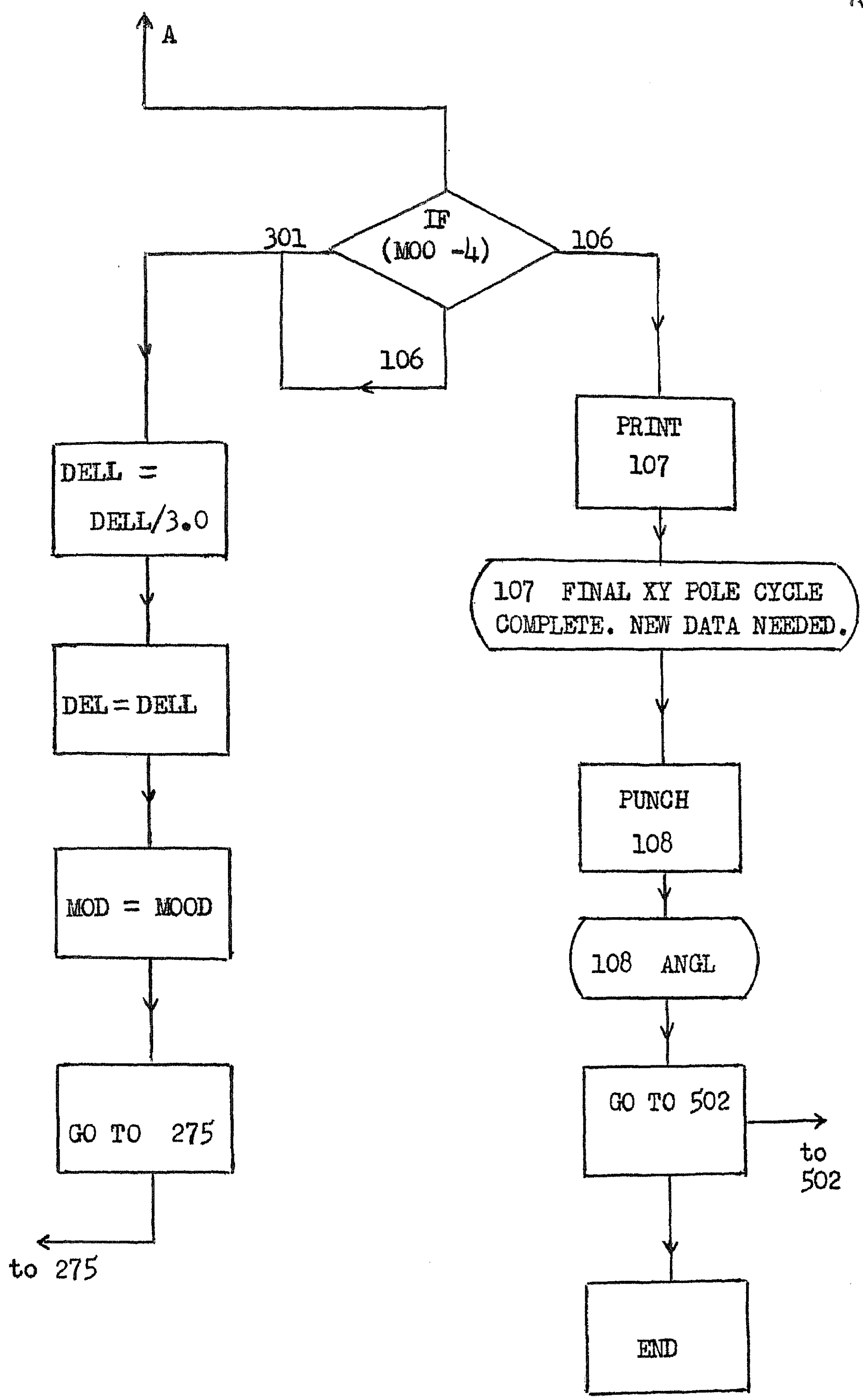

A
IF (SENSE SW.) 1
on 20
off 21
20 PRINT 3
ACCEPT CONST, FB
21 F = K
22
IF(INDEX)
23
22
N = N + 1
NSFP NSFP + 1
to 23
23
IF(NF -N)
25
to 23
25
FEE = FEE + ATANF ((Y(N)-F)/X(N))
to 22
22
IF(NSFP-NF)
24
24
FE(K) = FEE
to 23
A
B
PUNCH INDIX, PHASE ERRORS.
555
IF(NI)
556
MM = M GO TO 557
555
MM = M - 1
557 IF(NV-MM)
to 300
to 255
to 255


23
A
NN = NN + 1
NSVP =
NSVP + 1
FEEE = FEEE + ATANF
((YY(NN)-F)/XX(NN))
to
23
IF
(NSVP-NV)
13
13
13
IF(NF)
15
14
14
ANG(K) =
FEEE
ANG(K) =
FE(K)+ FEEE
GO TO
16
FEE = 0.
FEEE = 0.
N = I
NN = NI
NSFP = NE
NSVP = NNE
998
ANGL =
ANG(1)
IF(INDEX)
999
998
to 999
A
to 999
A


A
999
ERR(K) = ANG(K) -ANGL*F
DELTA = CONST*ERR(K)* (FB - F)
DELTA = ABSF(DELTA)
ERFNC = ERFNC+DELTA
JERR(K) = 1000*ERR(K)
60
58
IF(JERR(K))
62
IF (ERNEG ERR(K))
IF (ERR(K) - POSER)
61
62
62
62
62
59
ERNEG = -ERR(K)
POSER = ERR(K)
NEGFQ = K
KOSFQ = K
63
62
65
IF(K-100)
64
to 63
A
B
to 64
to 65
C


A
K = K + 1
GO TO 21
to
21
B
INDEX =
INDEX + 1
PUNCH INDEX, POSER,
KOSFQ, ERNEG, NEGFQ
Punch location of
movable poles
PUNCH ERFNC, REFER
IF
ERFNC - REFER
333
251
333
K LUNK =
KLUNK + 1
GO TO 252
C
PRINT 104
Frequency exceeds
100
PAUSE
GO TO 502
to
502
251
IF (KLUNK)
258
259
258
MOD =
MOD + 1
DEL = -DEL
KLUNK =
KLUNK + 1
GO TO 252
to
252
IF
(MOD - 3)
249
264
264
DEL =
-DEL/3.
DEL = -DEL
GO TO 275
252
REFER =
ERFNC
ERRA =
ERR(5)
etc.
275
ERFNC = 0.
A


A
POSER = 0.
ERNEG = 0.
KOSFQ = 0
NEGFQ = 0
GO TO
(253,260,280...300), M
300
253
265
to
10
GO TO 10
XX(1) =
XX(1) + DEL
etc.
YY(8)=YY(8)
+DEL
etc.
300
M = NI+1
PRINT 77
XY POLE SHIFT CYCLE COMPLETE
COW =
COW + 1.
IF
(COW - 1.5)
5
6
5
MOO =
MOO + 1
MOOD =
MOOD + 1
A


A
IF
(MOO -4)
301
106
106
DELL =
DELL/3.0
DEL = DELL
MOD = MOOD
GO TO 275
to 275
PRINT
107
107 FINAL XY POLE CYCLE
COMPLETE. NEW DATA NEEDED.
PUNCH
108
108 ANGL
GO TO 502
to
502
END

TRIMMING TEST ON TUNER DESIGN. MAY 7, 1965.

```
           1 2.123E-02          56 1.750E-01       100
100.000   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
             83.811              1715.966
           2 3.260E-02          57 1.617E-01       100
102.700   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
            111.874                83.811
           3 2.885E-02          57 1.661E-01       100
101.800   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
            102.341               111.874
           4 2.506E-02          57 1.705E-01       100
100.900   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
             92.968               102.341
           5 2.123E-02          56 1.750E-01       100
100.000   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
             83.811                92.968
           6 1.736E-02          56 1.795E-01       100
 99.100   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
             76.497                83.811
           7 1.345E-02          56 1.841E-01       100
 98.200   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
             72.439                76.497
           8 9.494E-03          55 1.887E-01       100
 97.300   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
             71.790                72.439
           9 5.503E-03          55 1.933E-01       100
 96.400   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
             74.858                71.790
          10 6.840E-03          55 1.918E-01       100
 96.700   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
             73.393                74.858
          11 8.170E-03          55 1.902E-01       100
 97.000   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
             72.375                73.393
          12 9.494E-03          55 1.887E-01       100
 97.300   99.000   99.000 154.000 154.000
  0.000   30.500  -30.500 107.000-107.000
             71.790                72.375
          13 1.081E-02          55 1.871E-01       100
```

```
97.600   99.000   99.000 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
          71.627                71.790
      14 1.213E-02          56 1.856E-01         100
97.900   99.000   99.000 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
          71.839                71.627
   13-1.194E-03-2.171E-03-2.728E-03-2.699E-03-1.967E-03-4.894E-04
 1.680E-03 4.357E-03 7.191E-03 9.618E-03 1.081E-02 9.642E-03 4.672E-0
-5.760E-03-2.328E-02-4.895E-02-8.236E-02-1.206E-01-1.582E-01-1.871E-0
      15 3.068E-02          58 1.615E-01         100
97.600 101.700 101.700 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
         103.312                71.627
      16 1.081E-02          55 1.871E-01         100
97.600   99.000   99.000 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
          71.627               103.312
      17 0.000E-99           0 2.134E-01         100
97.600   96.300   96.300 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
         122.869                71.627
      18 0.000E-99           0 2.046E-01         100
97.600   97.200   97.200 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
          96.319               122.869
      19 4.153E-03          55 1.958E-01         100
97.600   98.100   98.100 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
          76.518                96.319
      20 1.081E-02          55 1.871E-01         100
97.600   99.000   99.000 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
          71.627                76.518
      21 1.746E-02          56 1.785E-01         100
97.600   99.900   99.900 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
          75.934                71.627
      22 1.525E-02          56 1.814E-01         100
97.600   99.600   99.600 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
          73.577                75.934
      23 1.303E-02          56 1.842E-01         100
97.600   99.300   99.300 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
          72.129                73.577
      24 1.081E-02          55 1.871E-01         100
97.600   99.000   99.000 154.000 154.000
 0.000   30.500  -30.500 107.000-107.000
          71.627                72.129
```

```
          25 8.001E-03             55 1.900E-01         100
 97.600  98.700  98.700 154.000 154.000
  0.000  30.500 -30.500 107.000-107.000
             72.123                 71.627
       24-1.194E-03-2.171E-03-2.728E-03-2.699E-03-1.967E-03-4.894E-04
 1.689E-03 4.357E-03 7.191E-03 9.618E-03 1.081E-02 9.642E-03 4.672E-03
-5.767E-03-2.328E-02-4.895E-02-8.236E-02-1.206E-01-1.582E-01-1.871E-01
          26 2.129E-02             56 1.785E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  33.200 -33.200 107.000-107.000
             87.565                 71.627
          27 1.081E-02             55 1.871E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  30.500 -30.500 107.000-107.000
             71.627                 87.565
          28 1.114E-03             55 1.951E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  27.800 -27.800 107.000-107.000
             63.871                 71.627
          29 4.261E-03             55 1.925E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  28.700 -28.700 107.000-107.000
             76.775                 83.871
          30 7.494E-03             55 1.899E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  29.600 -29.600 107.000-107.000
             72.762                 76.775
          31 1.081E-02             55 1.871E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  30.500 -30.500 107.000-107.000
             71.627                 72.762
          32 1.422E-02             56 1.843E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  31.400 -31.400 107.000-107.000
             73.489                 71.627
          33 1.307E-02             56 1.853E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  31.100 -31.100 107.000-107.000
             72.523                 73.489
          34 1.193E-02             56 1.862E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  30.800 -30.800 107.000-107.000
             71.889                 72.523
          35 1.081E-02             55 1.871E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  30.500 -30.500 107.000-107.000
             71.627                 71.889
          36 9.696E-03             55 1.880E-01         100
 97.600  99.000  99.000 154.000 154.000
  0.000  30.200 -30.200 107.000-107.000
```

```
             71.671                   71.627                              150
     35-1.194E-03-2.171E-03-2.728E-03-2.699E-03-1.967E-03-4.894E-04
  1.680E-03 4.357E-03 7.191E-03 9.618E-03 1.081E-02 9.642E-03 4.672E-03
 -5.760E-03-2.328E-02-4.695E-02-8.236E-02-1.206E-01-1.582E-01-1.871E-01
          37 1.433E-02           56 1.796E-01          100                154
   97.600   99.000   99.000 156.700 156.700                               155
    0.000   30.500  -30.500 107.000-107.000                               156
             71.792                   71.627                              157
          38 1.081E-02           55 1.871E-01          100                158
   97.600   99.000   99.000 154.000 154.000                               159
    0.000   30.500  -30.500 107.000-107.000                               160
             71.627                   71.792                              161
          39 7.382E-03           55 1.948E-01          100                162
   97.600   99.000   99.000 151.300 151.300                               163
    0.000   30.500  -30.500 107.000-107.000                               164
             73.537                   71.627                              165
          40 8.523E-03           55 1.922E-01          100                166
   97.600   99.000   99.000 152.200 152.200                               167
    0.000   30.500  -30.500 107.000-107.000                               168
             72.643                   73.537                              169
          41 9.666E-03           55 1.897E-01          100                170
   97.600   99.000   99.000 153.100 153.100                               171
    0.000   30.500  -30.500 107.000-107.000                               172
             72.010                   72.643                              173
          42 1.081E-02           55 1.871E-01          100                174
   97.600   99.000   99.000 154.000 154.000                               175
    0.000   30.500  -30.500 107.000-107.000                               176
             71.627                   72.010                              177
          43 1.198E-02           56 1.846E-01          100                178
   97.600   99.000   99.000 154.900 154.900                               179
    0.000   30.500  -30.500 107.000-107.000                               180
             71.460                   71.627                              181
          44 1.315E-02           56 1.821E-01          100                182
   97.600   99.000   99.000 155.800 155.800                               183
    0.000   30.500  -30.500 107.000-107.000                               184
             71.501                   71.460                              185
          45 1.276E-02           56 1.829E-01          100                186
   97.600   99.000   99.000 155.500 155.500                               187
    0.000   30.500  -30.500 107.000-107.000                               188
             71.471                   71.501                              189
          46 1.237E-02           56 1.838E-01          100                190
   97.600   99.000   99.000 155.200 155.200                               191
    0.000   30.500  -30.500 107.000-107.000                               192
             71.459                   71.471                              193
          47 1.198E-02           56 1.846E-01          100                194
   97.600   99.000   99.000 154.900 154.900                               195
    0.000   30.500  -30.500 107.000-107.000                               196
             71.460                   71.459                              197
     46-1.074E-03-1.930E-03-2.365E-03-2.209E-03-1.347E-03 2.658E-04
  2.576E-03 5.401E-03 8.390E-03 1.097E-02 1.234E-02 1.135E-02 6.568E-03
 -3.672E-03-2.099E-02-4.645E-02-7.965E-02-1.177E-01-1.550E-01-1.838E-01
```

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          48 1.983E-02          57 1.726E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 109.700-109.700
                 77.730                71.459
          49 1.237E-02          56 1.838E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 107.000-107.000
                 71.459                77.730
          50 5.019E-03          55 1.948E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 104.300-104.300
                 75.272                71.459
          51 7.462E-03          55 1.911E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 105.200-105.200
                 72.716                75.272
          52 9.903E-03          55 1.874E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 106.100-106.100
                 71.479                72.716
          53 1.237E-02          56 1.838E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 107.000-107.000
                 71.459                71.479
          54 1.485E-02          56 1.800E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 107.900-107.900
                 72.525                71.459
          55 1.402E-02          56 1.813E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 107.600-107.600
                 72.050                72.525
          56 1.320E-02          56 1.825E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 107.300-107.300
                 71.674                72.050
          57 1.237E-02          56 1.838E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 107.000-107.000
                 71.459                71.674
          58 1.154E-02          56 1.850E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 106.700-106.700
                 71.330                71.459
          59 1.072E-02          56 1.862E-01          100
     97.600   99.000   99.000 155.200 155.200
      0.000   30.500  -30.500 106.400-106.400
                 71.351                71.330
      58-1.153E-03-2.088E-03-2.600E-03-2.523E-03-1.737E-03-1.991E-04
    2.037E-03 4.790E-03 7.709E-03 1.023E-02 1.153E-02 1.047E-02 5.634E-03
  -4.660E-03-2.203E-02-4.754E-02-8.078E-02-1.189E-01-1.562E-01-1.850E-01
                 END OF POLE SHIFT CYCLE.
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      60 1.550E-02              56 1.804E-01          100
  98.500   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          73.595                    71.330
      61 1.154E-02              56 1.850E-01          100
  97.600   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          71.330                    73.595
      62 7.558E-03              55 1.896E-01          100
  96.700   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          72.556                    71.330
      63 8.888E-03              55 1.881E-01          100
  97.000   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          71.747                    72.556
      64 1.021E-02              56 1.865E-01          100
  97.300   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          71.348                    71.747
      65 1.154E-02              56 1.850E-01          100
  97.600   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          71.330                    71.348
      66 1.287E-02              56 1.835E-01          100
  97.900   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          71.719                    71.330
      67 1.243E-02              56 1.840E-01          100
  97.800   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          71.550                    71.719
      68 1.199E-02              56 1.845E-01          100
  97.700   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          71.424                    71.550
      69 1.154E-02              56 1.850E-01          100
  97.600   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          71.330                    71.424
      70 1.110E-02              56 1.855E-01          100
  97.500   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          71.288                    71.330
      71 1.066E-02              56 1.860E-01          100
  97.400   99.000   99.000 155.200 155.200
   0.000   30.500  -30.500 106.700-106.700
          71.295                    71.288
   70-1.2[illegible]6E-03-2.192E-03-2.754E-03-2.724E-03-1.983E-03-4.871E-04
 1.712E-03 4.430E-03 7.319E-03 9.815E-03 1.109E-02 1.001E-02 5.161E-03
-5.146E-03-2.253E-02-4.804E-02-8.128E-02-1.194E-01-1.567E-01-1.855E-01
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        72 1.776E-02          56 1.769E-01         100                305
 97.500   99.900   99.900 155.200 155.200                             306
  0.000   30.500  -30.500 106.700-106.700                             307
           75.717                 71.288                              308
        73 1.110E-02          56 1.855E-01         100                309
 97.500   99.000   99.000 155.200 155.200                             310
  0.000   30.500  -30.500 106.700-106.700                             311
           71.288                 75.717                              312
        74 4.432E-03          55 1.942E-01         100                313
 97.500   98.100   98.100 155.200 155.200                             314
  0.000   30.500  -30.500 106.700-106.700                             315
           75.931                 71.288                              316
        75 6.661E-03          55 1.913E-01         100                317
 97.500   98.400   98.400 155.200 155.200                             318
  0.000   30.500  -30.500 106.700-106.700                             319
           73.214                 75.931                              320
        76 8.881E-03          55 1.884E-01         100                321
 97.500   98.700   98.700 155.200 155.200                             322
  0.000   30.500  -30.500 106.700-106.700                             323
           71.729                 73.214                              324
        77 1.110E-02          56 1.855E-01         100                325
 97.500   99.000   99.000 155.200 155.200                             326
  0.000   30.500  -30.500 106.700-106.700                             327
           71.288                 71.729                              328
        78 1.333E-02          56 1.826E-01         100                329
 97.500   99.300   99.300 155.200 155.200                             330
  0.000   30.500  -30.500 106.700-106.700                             331
           71.837                 71.288                              332
        79 1.259E-02          56 1.836E-01         100                333
 97.500   99.200   99.200 155.200 155.200                             334
  0.000   30.500  -30.500 106.700-106.700                             335
           71.563                 71.837                              336
        80 1.185E-02          56 1.845E-01         100                337
 97.500   99.100   99.100 155.200 155.200                             338
  0.000   30.500  -30.500 106.700-106.700                             339
           71.373                 71.563                              340
        81 1.110E-02          56 1.855E-01         100                341
 97.500   99.000   99.000 155.200 155.200                             342
  0.000   30.500  -30.500 106.700-106.700                             343
           71.288                 71.373                              344
        82 1.036E-02          56 1.865E-01         100                345
 97.500   98.900   98.900 155.200 155.200                             346
  0.000   30.500  -30.500 106.700-106.700                             347
           71.332                 71.288                              348
  81-1.2[illegible]6E-03-2.192E-03-2.754E-03-2.724E-03-1.983E-03-4.871E-04
1.712E-03 4.430E-03 7.319E-03 9.815E-03 1.109E-02 1.001E-02 5.161E-03
-5.146E-03-2.253E-02-4.804E-02-8.128E-02-1.194E-01-1.567E-01-1.855E-01
        83 1.451E-02          56 1.827E-01         100                352
 97.500   99.000   99.000 155.200 155.200                             353
  0.000   31.400  -31.400 106.700-106.700                             354
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          73.239                71.288                         355
       84 1.110E-02          56 1.855E-01      100             356
97.500   99.000   99.000 155.200 155.200                       357
 0.000   30.500  -30.500 106.700-106.700                       358
          71.288                73.239                         359
       85 7.779E-03          56 1.882E-01      100             360
97.500   99.000   99.000 155.200 155.200                       361
 0.000   29.600  -29.600 106.700-106.700                       362
          72.327                71.288                         363
       86 8.879E-03          56 1.873E-01      100             364
97.500   99.000   99.000 155.200 155.200                       365
 0.000   29.900  -29.900 106.700-106.700                       366
          71.671                72.327                         367
       87 9.988E-03          56 1.864E-01      100             368
97.500   99.000   99.000 155.200 155.200                       369
 0.000   30.200  -30.200 106.700-106.700                       370
          71.327                71.671                         371
       88 1.110E-02          56 1.855E-01      100             372
97.500   99.000   99.000 155.200 155.200                       373
 0.000   30.500  -30.500 106.700-106.700                       374
          71.288                71.327                         375
       89 1.223E-02          56 1.846E-01      100             376
97.500   99.000   99.000 155.200 155.200                       377
 0.000   30.800  -30.800 106.700-106.700                       378
          71.599                71.288                         379
       90 1.185E-02          56 1.849E-01      100             380
97.500   99.000   99.000 155.200 155.200                       381
 0.000   30.700  -30.700 106.700-106.700                       382
          71.457                71.599                         383
       91 1.148E-02          56 1.852E-01      100             384
97.500   99.000   99.000 155.200 155.200                       385
 0.000   30.600  -30.600 106.700-106.700                       386
          71.348                71.457                         387
       92 1.110E-02          56 1.855E-01      100             388
97.500   99.000   99.000 155.200 155.200                       389
 0.000   30.500  -30.500 106.700-106.700                       390
          71.288                71.348                         391
       93 1.073E-02          56 1.858E-01      100             392
97.500   99.000   99.000 155.200 155.200                       393
 0.000   30.400  -30.400 106.700-106.700                       394
          71.266                71.288                         395
       94 1.036E-02          56 1.861E-01      100             396
97.500   99.000   99.000 155.200 155.200                       397
 0.000   30.300  -30.300 106.700-106.700                       398
          71.285                71.266                         399
 93-1.258E-03-2.295E-03-2.906E-03-2.921E-03-2.221E-03-7.614E-04
1.406E-03 4.100E-03 6.969E-03 9.451E-03 1.071E-02 9.642E-03 4.784E-03
-5.519E-03-2.289E-02-4.840E-02-8.163E-02-1.197E-01-1.570E-01-1.858E-01
       95 1.191E-02          56 1.833E-01      100             403
97.500   99.000   99.000 156.100 156.100                       404
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 0.000   30.400  -30.400 106.700-106.700                                405
             71.065                     71.266                          406
         96 1.310E-02         56 1.808E-01          100                 407
97.500   99.000   99.000 157.000 157.000                                408
 0.000   30.400  -30.400 106.700-106.700                                409
             71.055                     71.065                          410
         97 1.429E-02         56 1.782E-01          100                 411
97.500   99.000   99.000 157.900 157.900                                412
 0.000   30.400  -30.400 106.700-106.700                                413
             71.311                     71.055                          414
         98 1.389E-02         56 1.791E-01          100                 415
97.500   99.000   99.000 157.600 157.600                                416
 0.000   30.400  -30.400 106.700-106.700                                417
             71.207                     71.311                          418
         99 1.350E-02         56 1.799E-01          100                 419
97.500   99.000   99.000 157.300 157.300                                420
 0.000   30.400  -30.400 106.700-106.700                                421
             71.130                     71.207                          422
        100 1.310E-02         56 1.808E-01          100                 423
97.500   99.000   99.000 157.000 157.000                                424
 0.000   30.400  -30.400 106.700-106.700                                425
             71.055                     71.130                          426
        101 1.270E-02         56 1.816E-01          100                 427
97.500   99.000   99.000 156.700 156.700                                428
 0.000   30.400  -30.400 106.700-106.700                                429
             71.040                     71.055                          430
        102 1.231E-02         56 1.824E-01          100                 431
97.500   99.000   99.000 156.400 156.400                                432
 0.000   30.400  -30.400 106.700-106.700                                433
             71.037                     71.040                          434
        103 1.191E-02         56 1.833E-01          100                 435
97.500   99.000   99.000 156.100 156.100                                436
 0.000   30.400  -30.400 106.700-106.700                                437
             71.065                     71.037                          438
        104 1.205E-02         56 1.830E-01          100                 439
97.500   99.000   99.000 156.200 156.200                                440
 0.000   30.400  -30.400 106.700-106.700                                441
             71.055                     71.065                          442
        105 1.218E-02         56 1.827E-01          100                 443
97.500   99.000   99.000 156.300 156.300                                444
 0.000   30.400  -30.400 106.700-106.700                                445
             71.046                     71.055                          446
        106 1.231E-02         56 1.824E-01          100                 447
97.500   99.000   99.000 156.400 156.400                                448
 0.000   30.400  -30.400 106.700-106.700                                449
             71.037                     71.046                          450
        107 1.244E-02         56 1.822E-01          100                 451
97.500   99.000   99.000 156.500 156.500                                452
 0.000   30.400  -30.400 106.700-106.700                                453
             71.038                     71.037                          454
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 106-1.136E-03-2.050E-03-2.537E-03-2.424E-03-1.592E-03 4.900E-06
 2.315E-03 5.15[illegible]E-03 8.162E-03 1.082E-02 1.226E-02 1.136E-02 6.693E-03
-3.417E-03-1.089E-02-4.509E-02-7.891E-02-1.168E-01-1.539E-01-1.824E-01
         108 1.475E-02          56 1.788E-01          100                458
 97.500  99.000  99.000 156.400 156.400                                  459
  0.000  30.400 -30.400 107.600-107.600                                  460
              71.957            71.037                                   461
         109 1.231E-02          56 1.824E-01          100                462
 97.500  99.000  99.000 156.400 156.400                                  463
  0.000  30.400 -30.400 106.700-106.700                                  464
              71.037            71.957                                   465
         110 [illegible].80[illegible]E-03          56 1.861E-01          100                466
 97.500  99.000  99.000 156.400 156.400                                  467
  0.000  30.400 -30.400 105.800-105.800                                  468
              71.187            71.037                                   469
         111 1.06[illegible]E-02          56 1.849E-01          100                470
 97.500  99.000  99.000 156.400 156.400                                  471
  0.000  30.400 -30.400 106.100-106.100                                  472
              71.012            71.187                                   473
         112 1.149E-02          56 1.836E-01          100                474
 97.500  99.000  99.000 156.400 156.400                                  475
  0.000  30.400 -30.400 106.400-106.400                                  476
              70.960            71.012                                   477
         113 1.231E-02          56 1.824E-01          100                478
 97.500  99.000  99.000 156.400 156.400                                  479
  0.000  30.400 -30.400 106.700-106.700                                  480
              71.037            70.960                                   481
         114 1.204E-02          56 1.828E-01          100                482
 97.500  99.000  99.000 156.400 156.400                                  483
  0.000  30.400 -30.400 106.600-106.600                                  484
              71.008            71.037                                   485
         115 1.177E-02          56 1.832E-01          100                486
 97.500  99.000  99.000 156.400 156.400                                  487
  0.000  30.400 -30.400 106.500-106.500                                  488
              70.979            71.008                                   489
         116 1.14[illegible]E-02          56 1.836E-01          100                490
 97.500  99.000  99.000 156.400 156.400                                  491
  0.000  30.400 -30.400 106.400-106.400                                  492
              70.960            70.979                                   493
         117 1.122E-02          56 1.841E-01          100                494
 97.500  99.000  99.000 156.400 156.400                                  495
  0.000  30.400 -30.400 106.300-106.300                                  496
              70.956            70.960                                   497
         118 1.095E-02          56 1.845E-01          100                498
 97.500  99.000  99.000 156.400 156.400                                  499
  0.000  30.400 -30.400 106.200-106.200                                  500
              70.970            70.956                                   501
 117-1.24[illegible]E-03-2.256E-03-2.847E-03-2.836E-03-2.105E-03-6.071E-04
 1.606E-03 4.354E-03 7.287E-03 9.842E-03 1.119E-02 1.021E-02 5.465E-03
-4.718E-03-1.196E-02-4.732E-02-8.040E-02-1.183E-01-1.555E-01-1.841E-01

              END OF POLE SHIFT CYCLE.
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PROGRAM RESTARTED WITH LAST POLE POSITIONS FROM ABOVE.

          1 2.579E-02          58 1.584E-01        100               512
97.500  99.000  99.000 156.400 156.400                               513
 0.000  30.400 -30.400 106.200-106.200                               514
             85.536                70.956                            515
          2 2.444E-02          58 1.600E-01        100               516
97.200  99.000  99.000 156.400 156.400                               517
 0.000  30.400 -30.400 106.200-106.200                               518
             82.301                85.536                            519
          3 2.308E-02          58 1.615E-01        100               520
96.900  99.000  99.000 156.400 156.400                               521
 0.000  30.400 -30.400 106.200-106.200                               522
             79.458                82.301                            523
          4 2.171E-02          58 1.631E-01        100               524
96.600  99.000  99.000 156.400 156.400                               525
 0.000  30.400 -30.400 106.200-106.200                               526
             76.918                79.458                            527
          5 2.033E-02          58 1.646E-01        100               528
96.300  99.000  99.000 156.400 156.400                               529
 0.000  30.400 -30.400 106.200-106.200                               530
             74.788                76.918                            531
          6 1.895E-02          58 1.662E-01        100               532
96.000  99.000  99.000 156.400 156.400                               533
 0.000  30.400 -30.400 106.200-106.200                               534
             72.964                74.788                            535
          7 1.757E-02          58 1.677E-01        100               536
95.700  99.000  99.000 156.400 156.400                               537
 0.000  30.400 -30.400 106.200-106.200                               538
             71.523                72.964                            539
          8 1.618E-02          57 1.693E-01        100               540
95.400  99.000  99.000 156.400 156.400                               541
 0.000  30.400 -30.400 106.200-106.200                               542
             70.397                71.523                            543
          9 1.479E-02          57 1.709E-01        100               544
95.100  99.000  99.000 156.400 156.400                               545
 0.000  30.400 -30.400 106.200-106.200                               546
             69.673                70.397                            547
         10 1.340E-02          57 1.724E-01        100               548
94.800  99.000  99.000 156.400 156.400                               549
 0.000  30.400 -30.400 106.200-106.200                               550
             69.277                69.673                            551
         11 1.200E-02          57 1.740E-01        100               552
94.500  99.000  99.000 156.400 156.400                               553
 0.000  30.400 -30.400 106.200-106.200                               554
             69.286                69.277                            555
         12 1.247E-02          57 1.735E-01        100               556
94.600  99.000  99.000 156.400 156.400                               557
 0.000  30.400 -30.400 106.200-106.200                               558
             69.256                69.286                            559
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        13 1.293E-02           57 1.730E-01        100                  560
  94.700   99.000   99.000 156.400 156.400                              561
   0.000   30.400  -30.400 106.200-106.200                              562
                69.250               69.256                             563
        14 1.340E-02           57 1.724E-01        100                  564
  94.800   99.000   99.000 156.400 156.400                              565
   0.000   30.400  -30.400 106.200-106.200                              566
                69.277               69.250                             567
     13-1.476E-03-2.705E-03-3.459E-03-3.544E-03-2.824E-03-1.237E-03
 1.173E-03 4.231E-03 7.590E-03 1.068E-02 1.268E-02 1.246E-02 8.562E-03
-6.819E-04-1.691E-02-4.118E-02-7.310E-02-1.098E-01-1.457E-01-1.730E-01
        15 1.519E-02           57 1.701E-01        100                  571
  94.700   99.300   99.300 156.400 156.400                              572
   0.000   30.400  -30.400 106.200-106.200                              573
                69.806               69.250                             574
        16 1.293E-02           57 1.730E-01        100                  575
  94.700   99.000   99.000 156.400 156.400                              576
   0.000   30.400  -30.400 106.200-106.200                              577
                69.250               69.806                             578
        17 1.067E-02           57 1.759E-01        100                  579
  94.700   98.700   98.700 156.400 156.400                              580
   0.000   30.400  -30.400 106.200-106.200                              581
                69.573               69.250                             582
        18 1.142E-02           57 1.749E-01        100                  583
  94.700   98.800   98.800 156.400 156.400                              584
   0.000   30.400  -30.400 106.200-106.200                              585
                69.345               69.573                             586
        19 1.218E-02           57 1.739E-01        100                  587
  94.700   98.900   98.900 156.400 156.400                              588
   0.000   30.400  -30.400 106.200-106.200                              589
                69.260               69.345                             590
        20 1.293E-02           57 1.730E-01        100                  591
  94.700   99.000   99.000 156.400 156.400                              592
   0.000   30.400  -30.400 106.200-106.200                              593
                69.250               69.260                             594
        21 1.369E-02           57 1.720E-01        100                  595
  94.700   99.100   99.100 156.400 156.400                              596
   0.000   30.400  -30.400 106.200-106.200                              597
                69.327               69.250                             598
     20-1.476E-03-2.705E-03-3.459E-03-3.544E-03-2.824E-03-1.237E-03
 1.173E-03 4.231E-03 7.590E-03 1.068E-02 1.268E-02 1.246E-02 8.562E-03
-6.819E-04-1.691E-02-4.118E-02-7.310E-02-1.098E-01-1.457E-01-1.730E-01
        22 1.406E-02           57 1.721E-01        100                  602
  94.700   99.000   99.000 156.400 156.400                              603
   0.000   30.700  -30.700 106.200-106.200                              604
                69.485               69.250                             605
        23 1.293E-02           57 1.730E-01        100                  606
  94.700   99.000   99.000 156.400 156.400                              607
   0.000   30.400  -30.400 106.200-106.200                              608
                69.250               69.485                             609
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       24 1.162E-02          57 1.739E-01       100                610
  94.700  99.000  99.000 156.400 156.400                           611
   0.000  30.100 -30.100 106.200-106.200                           612
           69.291                 69.250                           613
       25 1.219E-02          57 1.736E-01       100                614
  94.700  99.000  99.000 156.400 156.400                           615
   0.000  30.200 -30.200 106.200-106.200                           616
           69.245                 69.291                           617
       26 1.256E-02          57 1.733E-01       100                618
  94.700  99.000  99.000 156.400 156.400                           619
   0.000  30.300 -30.300 106.200-106.200                           620
           69.238                 69.245                           621
       27 1.293E-02          57 1.730E-01       100                622
  94.700  99.000  99.000 156.400 156.400                           623
   0.000  30.400 -30.400 106.200-106.200                           624
           69.250                 69.238                           625
    26-1.528E-03-2.898E-03-3.611E-03-3.741E-03-3.061E-03-1.510E-03
  8.689E-04 3.902E-03 7.241E-03 1.032E-02 1.231E-02 1.208E-02 8.187E-0
-1.054E-03-1.727E-02-4.153E-02-7.344E-02-1.101E-01-1.460E-01-1.733E-0
       28 1.297E-02          57 1.724E-01       100                629
  94.700  99.000  99.000 156.700 156.700                           630
   0.000  30.300 -30.300 106.200-106.200                           631
           69.162                 69.238                           632
       29 1.338E-02          57 1.716E-01       100                633
  94.700  99.000  99.000 157.000 157.000                           634
   0.000  30.300 -30.300 106.200-106.200                           635
           69.113                 69.162                           636
       30 1.379E-02          57 1.707E-01       100                637
  94.700  99.000  99.000 157.300 157.300                           638
   0.000  30.300 -30.300 106.200-106.200                           639
           69.107                 69.113                           640
       31 1.420E-02          58 1.699E-01       100                641
  94.700  99.000  99.000 157.600 157.600                           642
   0.000  30.300 -30.300 106.200-106.200                           643
           69.130                 69.107                           644
       32 1.406E-02          57 1.702E-01       100                645
  94.700  99.000  99.000 157.500 157.500                           646
   0.000  30.300 -30.300 106.200-106.200                           647
           69.121                 69.130                           648
       33 1.393E-02          57 1.705E-01       100                649
  94.700  99.000  99.000 157.400 157.400                           650
   0.000  30.300 -30.300 106.200-106.200                           651
           69.112                 69.121                           652
       34 1.379E-02          57 1.707E-01       100                653
  94.700  99.000  99.000 157.300 157.300                           654
   0.000  30.300 -30.300 106.200-106.200                           655
           69.107                 69.112                           656
       35 1.365E-02          57 1.710E-01       100                657
  94.700  99.000  99.000 157.200 157.200                           658
   0.000  30.300 -30.300 106.200-106.200                           659
```

```
            69.109                   69.107                           660
     34-1.435E-03-2.621E-03-3.328E-03-3.360E-03-2.580E-03-9.256E-04
   1.562E-03 4.708E-03 8.165E-03 1.137E-02 1.349E-02 1.339E-02 9.635E-(
  5.382E-04-1.553E-02-3.964E-02-7.139E-02-1.079E-01-1.436E-01-1.707E-(
        36 1.461E-02             58 1.695E-01          100            664
    94.700   99.000   99.000 157.300 157.300                          665
     0.000   30.300  -30.300 106.500-106.500                          666
            69.270                   69.107                           667
        37 1.379E-02             57 1.707E-01          100            668
    94.700   99.000   99.000 157.300 157.300                          669
     0.000   30.300  -30.300 106.200-106.200                          670
            69.107                   69.270                           671
        38 1.297E-02             57 1.719E-01          100            672
    94.700   99.000   99.000 157.300 157.300                          673
     0.000   30.300  -30.300 105.900-105.900                          674
            69.054                   69.107                           675
        39 1.215E-02             57 1.731E-01          100            676
    94.700   99.000   99.000 157.300 157.300                          677
     0.000   30.300  -30.300 105.600-105.600                          678
            69.119                   69.054                           679
        40 1.242E-02             57 1.727E-01          100            680
    94.700   99.000   99.000 157.300 157.300                          681
     0.000   30.300  -30.300 105.700-105.700                          682
            69.095                   69.119                           683
        41 1.270E-02             57 1.723E-01          100            684
    94.700   99.000   99.000 157.300 157.300                          685
     0.000   30.300  -30.300 105.800-105.800                          686
            69.074                   69.095                           687
        42 1.297E-02             57 1.719E-01          100            688
    94.700   99.000   99.000 157.300 157.300                          689
     0.000   30.300  -30.300 105.900-105.900                          700
            69.054                   69.074                           701
        43 1.324E-02             57 1.715E-01          100            702
    94.700   99.000   99.000 157.300 157.300                          703
     0.000   30.300  -30.300 106.000-106.000                          704
            69.055                   69.054                           705
     42-1.512E-03-2.775E-03-3.559E-03-3.667E-03-2.961E-03-1.380E-03
   1.035E-03 4.111E-03 7.500E-03 1.063E-02 1.269E-02 1.254E-02 8.723E-0
  -4.271E-04-1.654E-02-4.070E-02-7.249E-02-1.091E-01-1.448E-01-1.719E-0

             THIRD POLE SHIFT CYCLE COMPLETE.

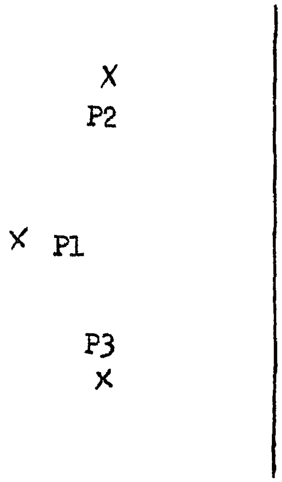
        44 1.344E-02             57 1.714E-01          100            712
    94.800   99.000   99.000 157.300 157.300                          713
     0.000   30.300  -30.300 105.900-105.900                          714
            69.083                   69.054                           715
        45 1.297E-02             57 1.719E-01          100            716
    94.700   99.000   99.000 157.300 157.300                          717
     0.000   30.300  -30.300 105.900-105.900                          718
            69.054                   69.083                           719
```

```
      46 1.25?E-02           57 1.725E-01      100            720
94.600   99.?00   99.000 157.300 157.300                      721
 0.?0?   30.300  -30.300 105.900-105.900                      722
          69.077              69.054                          723
   45-1.?12E-0?-2.775E-03-3.559E-03-3.667E-03-2.961E-03-1.380E-03
 1.?35E-0? 4.111E-03 7.500E-03 1.063E-02 1.269E-02 1.254E-02 8.723E-0?
-4.271E-04-1.604E-02-4.070E-02-7.249E-02-1.091E-01-1.448E-01-1.719E-01
      47 1.372E-02           57 1.710E-01      100            727
94.700   9?.100   99.100 157.300 157.300                      728
 0.000   30.3    -30.300 105.900-105.900                      729
          69.131              69.054                          730
      48 1.297E-02           57 1.719E-01      100            731
94.700   9?.?00   99.000 157.300 157.300                      732
 0.000   30.300  -30.300 105.900-105.900                      733
          69.054              69.131                          734
      49 1.221E-02           57 1.729E-01      100            735
94.700   98.900   98.900 157.300 157.300                      736
 0.000   30.300  -30.300 105.900-105.900                      737
          69.083              69.054                          738
   46-1.512E-03-2.775E-03-3.559E-03-3.667E-03-2.961E-03-1.380E-03
 1.035E-03 4.111E-03 7.500E-03 1.063E-02 1.269E-02 1.254E-02 8.723E-03
-4.271E-04-1.604E-02-4.070E-02-7.249E-02-1.091E-01-1.448E-01-1.719E-01
      50 1.304E-02           57 1.716E-01      100            742
94.700   99.?00   99.000 157.300 157.300                      743
 0.000   30.400  -30.400 105.900-105.900                      744
          69.059              69.054                          745
      51 1.297E-02           57 1.719E-01      100            746
94.700   99.000   99.000 157.300 157.300                      747
 0.000   30.300  -30.300 105.900-105.900                      748
          69.054              69.089                          749
      52 1.260E-02           57 1.723E-01      100            750
94.700   99.000   99.000 157.300 157.300                      751
 0.000   30.200  -30.200 105.900-105.900                      752
          69.060              69.054                          753
   51-1.512E-03-2.775E-03-3.559E-03-3.667E-03-2.961E-03-1.380E-03
 1.035E-03 4.111E-03 7.500E-03 1.063E-02 1.269E-02 1.254E-02 8.723E-03
-4.271E-04-1.604E-02-4.070E-02-7.249E-02-1.091E-01-1.448E-01-1.719E-01
      53 1.311E-02           57 1.717E-01      100            757
94.700   99.000   99.000 157.400 157.400                      758
 0.000   30.300  -30.300 105.900-105.900                      759
          69.034              69.054                          760
      54 1.324E-02           57 1.714E-01      100            761
94.700   99.000   99.000 157.500 157.500                      762
 0.000   30.300  -30.300 105.900-105.900                      763
          69.018              69.034                          764
      55 1.348E-02           57 1.711E-01      100            765
94.700   99.300   99.000 157.600 157.600                      766
 0.000   30.300  -30.300 105.900-105.900                      767
          69.010              69.018                          768
      56 1.352E-02           57 1.708E-01      100            769
```

```
94.700  99.000  99.000 157.700 157.700                      770
 0.000  30.300 -30.300 105.900-105.900                      771
         69.208                 69.010                      772
    57 1.366E-02           57 1.705E-01          100        773
94.700  99.000  99.000 157.800 157.800                      774
 0.000  30.300 -30.300 105.900-105.900                      775
         69.006                 69.008                      776
    58 1.379E-02           57 1.702E-01          100        777
94.700  99.000  99.000 157.900 157.900                      778
 0.000  30.300 -30.300 105.900-105.900                      790
         69.004                 69.006                      791
    57 1.3[illegible]E-02           58 1.700E-01          100        792
94.700  99.000  99.000 158.000 158.000                      793
 0.000  30.300 -30.300 105.900-105.900                      794
         69.003                 69.004                      795
    60 1.407E-02           58 1.697E-01          100        796
94.700  99.000  99.000 158.100 158.100                      797
 0.000  30.300 -30.300 105.900-105.900                      798
         69.010                 69.003                      799
  59-1.4[illegible]E-03-2.628E-03-3.336E-03-3.367E-03-2.565E-03-9.200E-04
1.580E-03 4.744E-03 8.225E-03 1.146E-02 1.361E-02 1.356E-02 9.857E-(
8.184[illegible]-1.518E-02-3.922E-02-7.089E-02-1.073E-01-1.430E-01-1.700E-0.
    61 1.4[illegible]1E-02           58 1.696E-01          100        803
94.700  99.000  99.000 158.000 158.000                      804
 0.000  30.300 -30.300 106.000-106.000                      805
         69.056                 69.003                      806
    62 1.398E-02           58 1.700E-01          100        807
94.700  99.000  99.000 158.000 158.000                      808
 0.000  30.300 -30.300 105.900-105.900                      809
         69.003                 69.056                      810
    63 1.366E-02           57 1.704E-01          100        811
94.700  99.000  99.000 158.000 158.000                      812
 0.000  30.300 -30.300 105.800-105.800                      813
         68.973                 69.003                      814
    64 1.339E-02           57 1.708E-01          100        815
94.700  99.000  99.000 158.000 158.000                      816
 0.000  30.300 -30.300 105.700-105.700                      817
         68.942                 68.973                      818
    65 1.312E-02           57 1.712E-01          100        819
94.700  99.000  99.000 158.000 158.000                      820
 0.000  30.300 -30.300 105.600-105.600                      821
         68.924                 68.942                      822
    66 1.2[illegible]E-02           57 1.716E-01          100        823
94.700  99.000  99.000 158.000 158.000                      824
 0.000  30.300 -30.300 105.500-105.500                      825
         68.945                 68.924                      826
  65-1.515E-03-2.781E-03-3.565E-03-3.672E-03-2.961E-03-1.371E-03        827
1.057E-03 4.152E-03 7.565E-03 1.073E-02 1.283E-02 1.271E-02 8.952E-03   828
-1.391E-04-1.619E-02-4.027E-02-7.199E-02-1.085E-01-1.441E-01-1.712E-01  829
-69.830110E-03                                                          830
```

NOTE: The last four cards from the output data were accidentally lost. The above data was copied from an earlier printout of the same data.

THREE POLE PURE RIMO FILTER



normalized pole locations

P1	99.900	+	j0.000
P2	75.000	+	j75.000
P3	75.000		-j75.000

COMPUTER PROGRAM INPUT, CONTROL VARIABLES

NF...0

NV...3

I..0

NI...0

MOOD...0

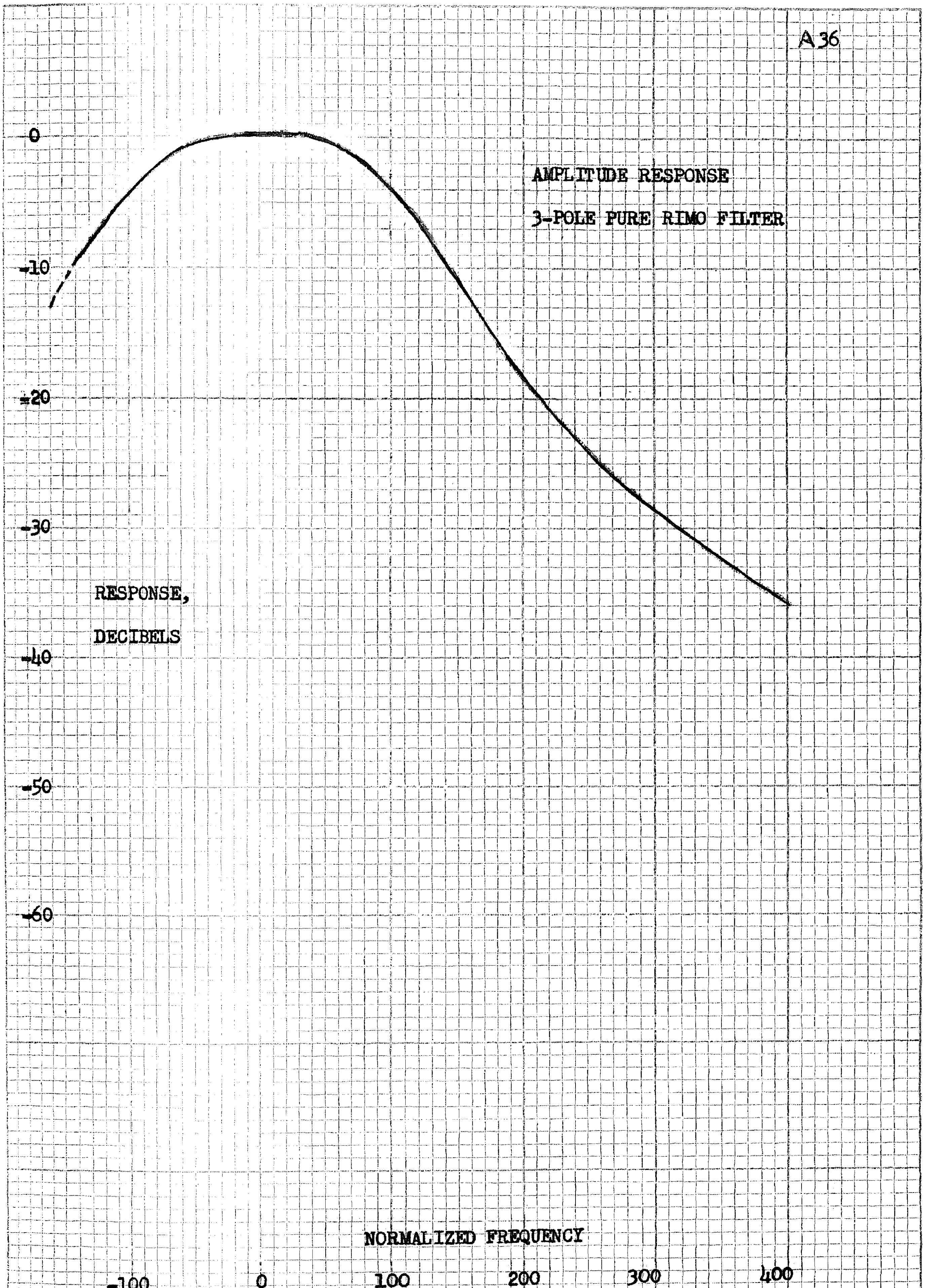
DELL...2.7

COW..0

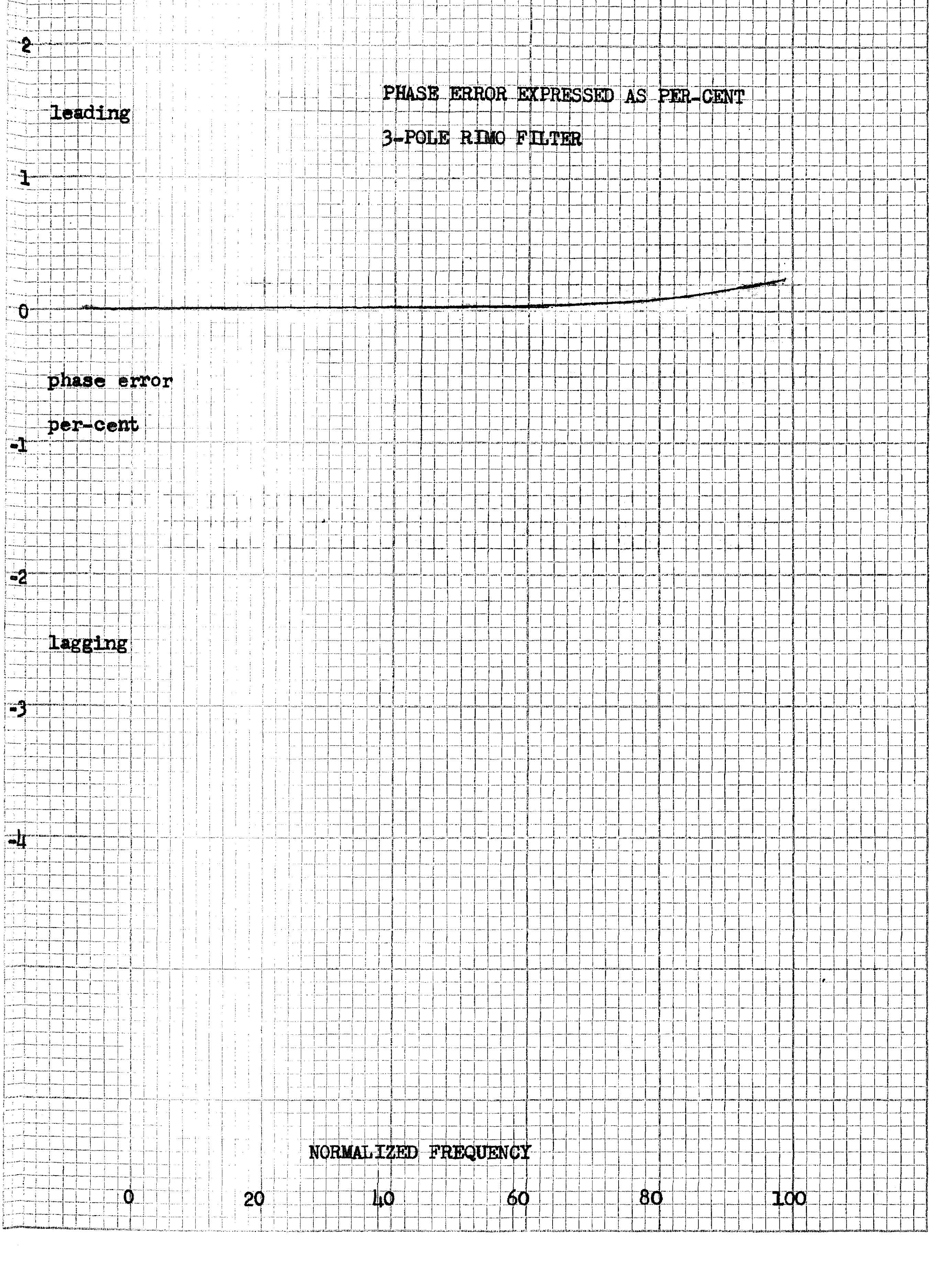
MOO..0.

FB .... 110.

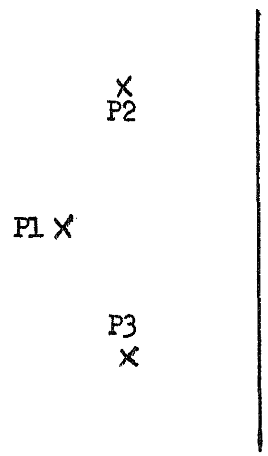
CONST 1.0



A 36
AMPLITUDE RESPONSE
3-POLE PURE RIMO FILTER
0
-10
-20
-30
-40
-50
-60
RESPONSE,
DECIBELS
NORMALIZED FREQUENCY
-100
0
100
200
300
400


PHASE ERROR EXPRESSED AS PER-CENT
3-POLE RIMO FILTER
2
leading
1
0
phase error
per-cent
-1
-2
lagging
-3
-4
NORMALIZED FREQUENCY
0
20
40
60
80
100

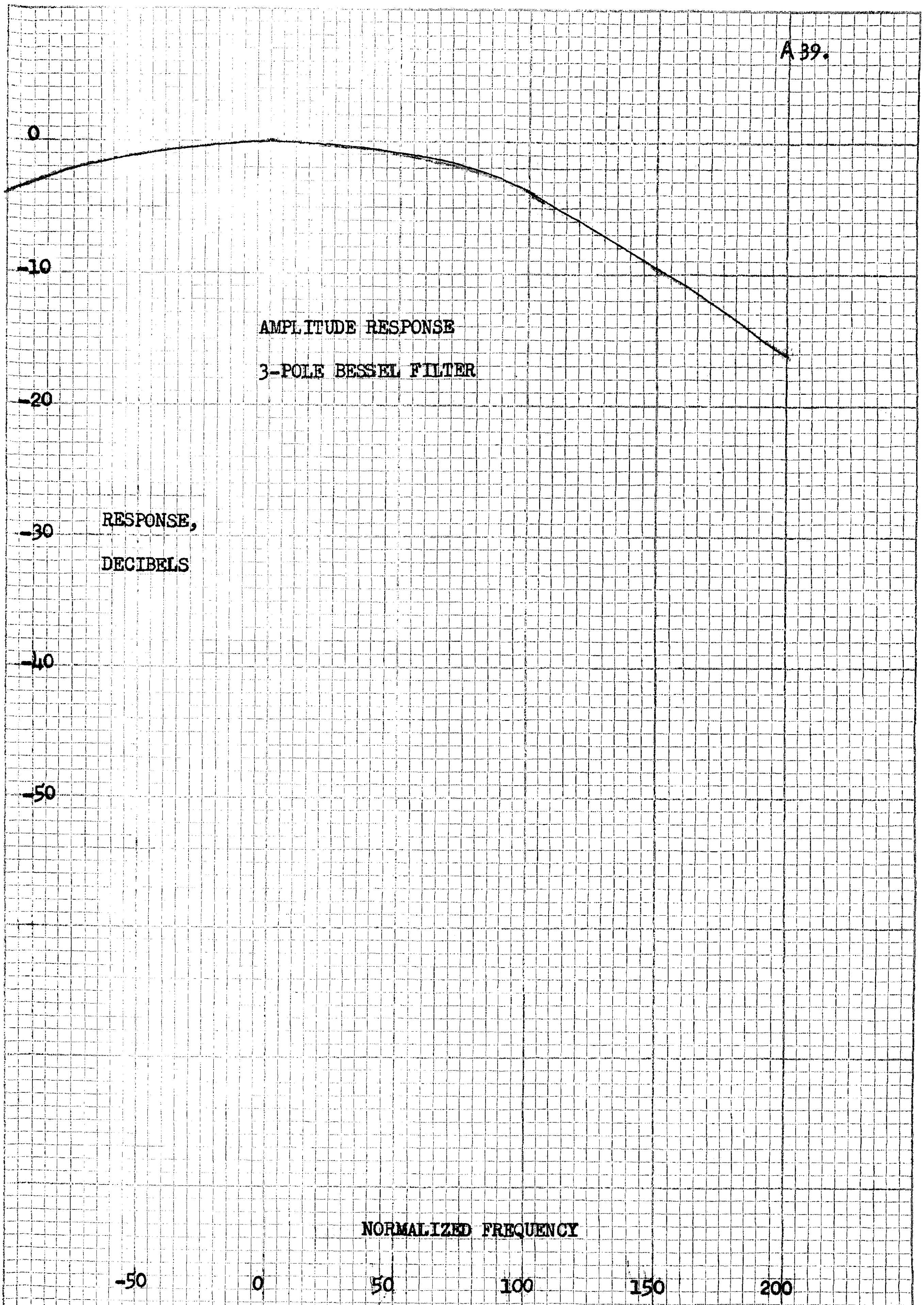
THREE POLE BESSEL FILTER

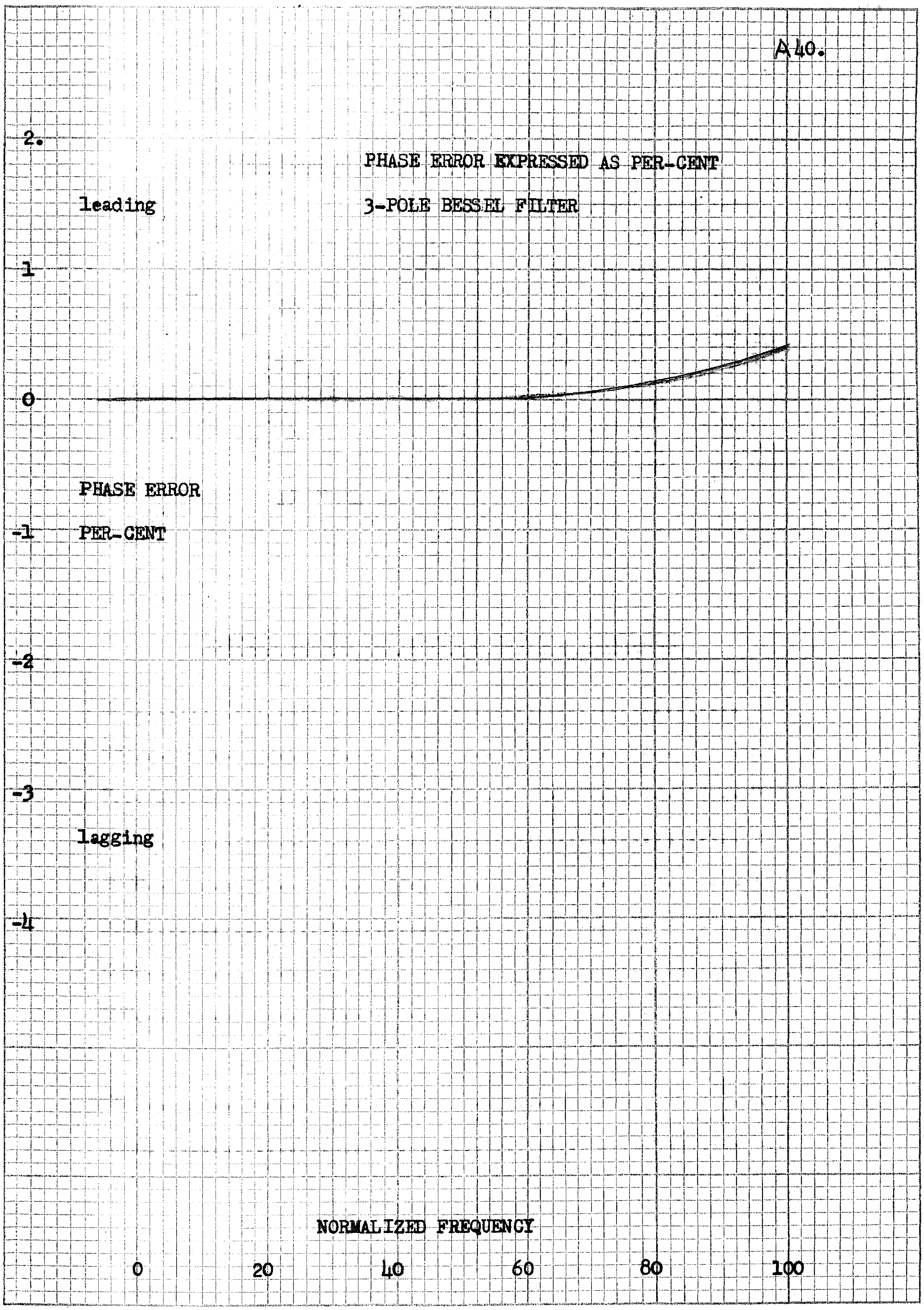


normalized pole locations

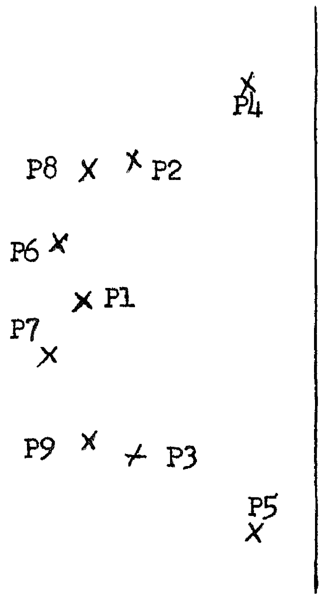
P1	100.000	+ j0.000
P2	79.100	+ j75.500
P3	79.100	-j75.500

NOTE: The pole locations for this filter were fed into the computer as initial data for locating the poles of a three pole pure Rimo filter (the filter of appendix, p. 35.)


0
-10
-20
-30
-40
-50
AMPLITUDE RESPONSE
3-POLE BESSEL FILTER
RESPONSE,
DECIBELS
NORMALIZED FREQUENCY
-50
0
50
100
150
200


PHASE ERROR EXPRESSED AS PER-CENT
3-POLE BESSEL FILTER
2.
leading
1
0
PHASE ERROR
PER-CENT
-1
-2
-3
lagging
-4
NORMALIZED FREQUENCY
0
20
40
60
80
100

NINE POLE HYBRID RIMO FILTER



normalized pole locations

P1	100.000	+ j0.000
P2	80.902	+ j58.779
P3	80.902	-j58.779
P4	30.902	+ j95.106
P5	30.902	-j95.106
P6	107.900	+ j20.400
P7	107.900	-j20.400
P8	102.300	+ j55.000
P9	102.300,	-j55.000

INITIAL VALUES FOR PROGRAM CONTROL VARIABLES

NF.. 5

NV.. 4

I... 0

NI.. 1

MOOD.. 1

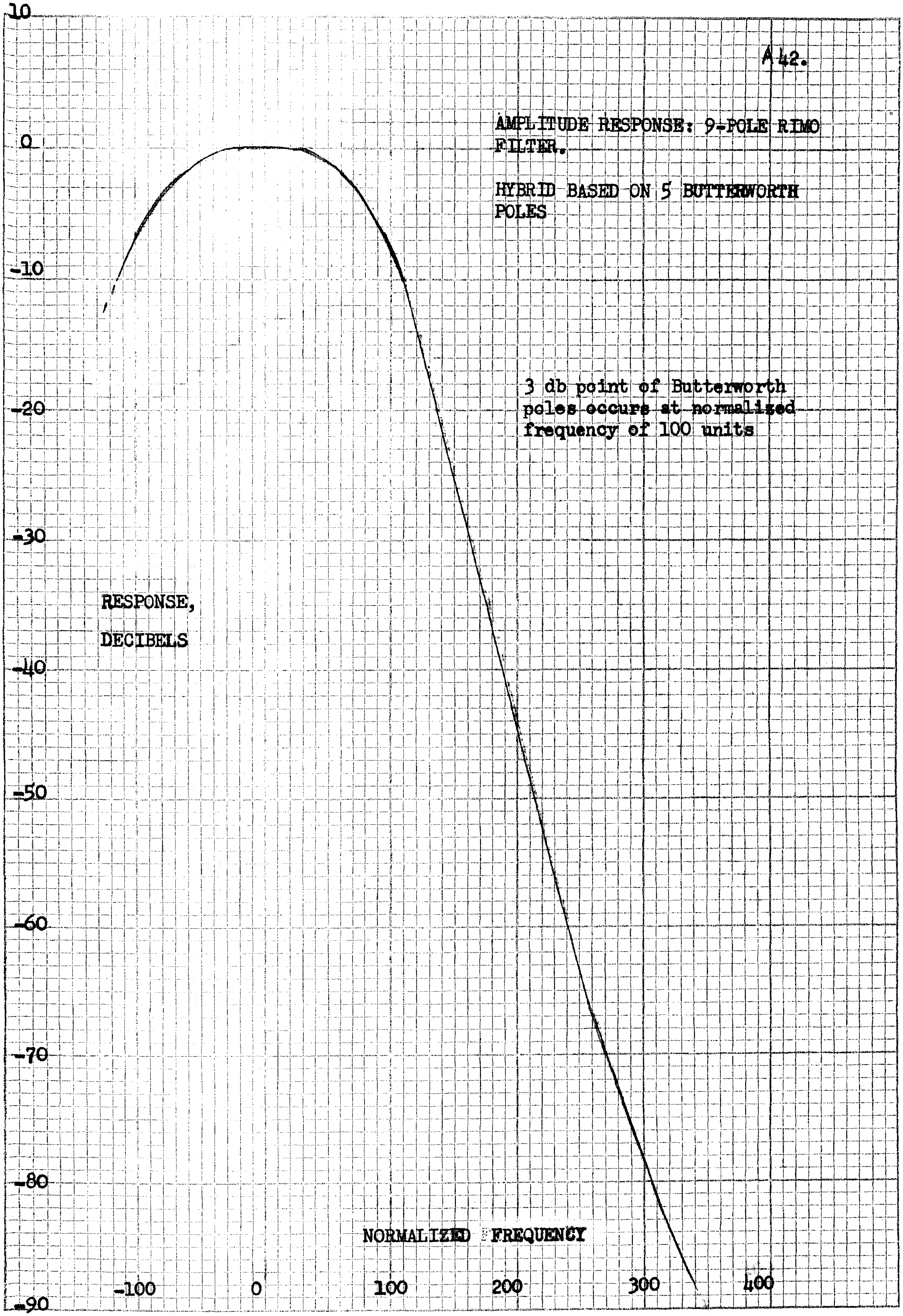
DELL.. 2.7

COW... -2.

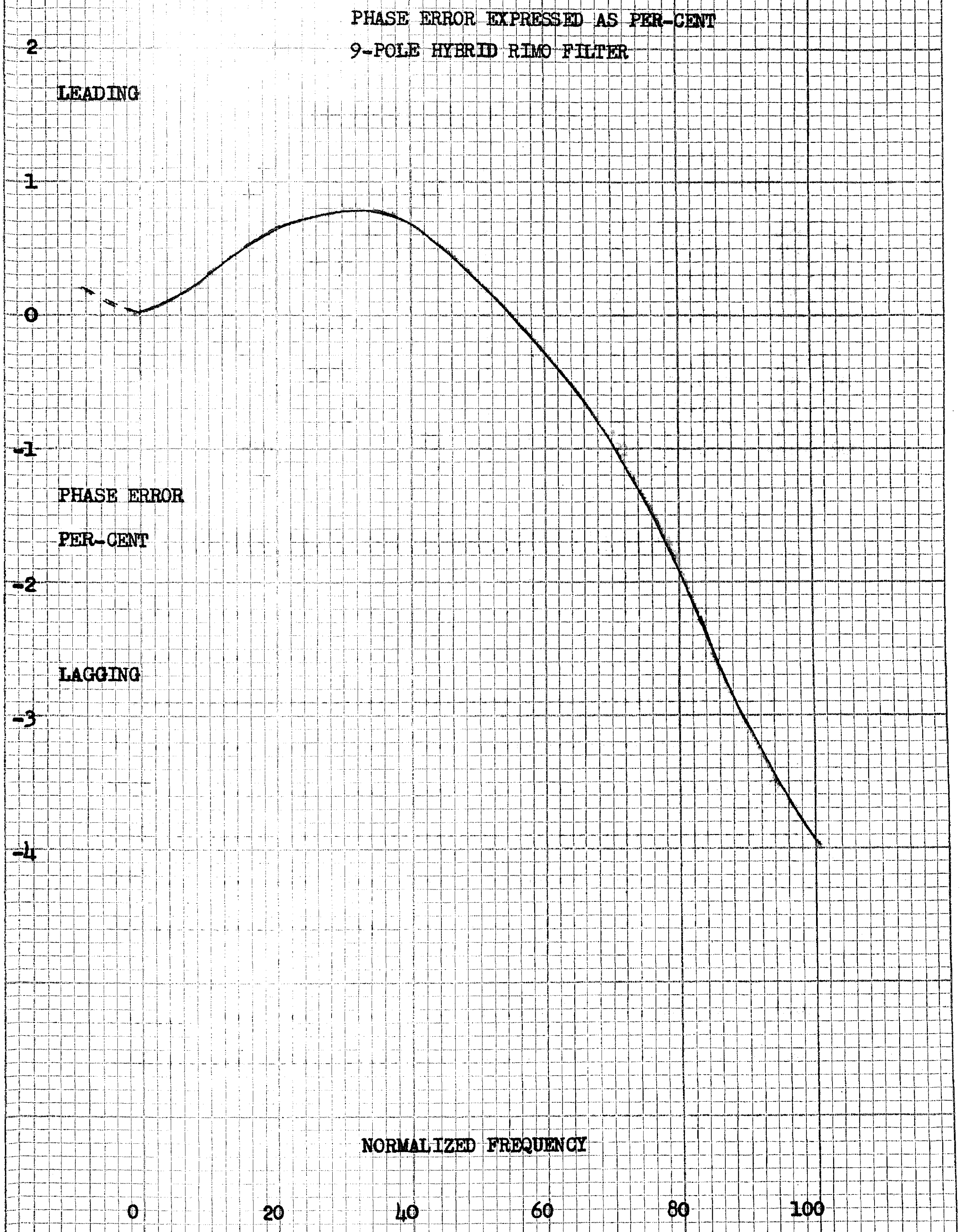
MOO... 0.

FB .... 110.

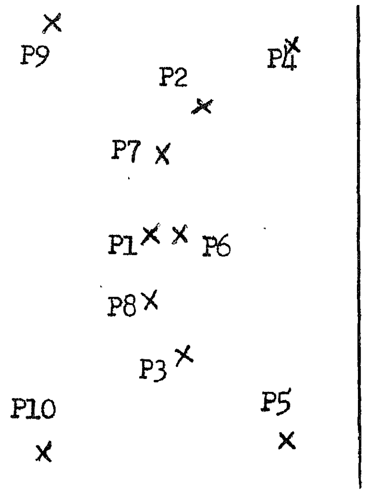
CONST 1.0



AMPLITUDE RESPONSE: 9-POLE RIMO FILTER.
HYBRID BASED ON 5 BUTTERWORTH POLES
3 db point of Butterworth poles occurs at normalized frequency of 100 units
RESPONSE, DECIBELS
NORMALIZED FREQUENCY
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
0
100
200
300
400


PHASE ERROR EXPRESSED AS PER-CENT
9-POLE HYBRID RIMO FILTER
2
LEADING
1
0
-1
PHASE ERROR
PER-CENT
-2
LAGGING
-3
-4
NORMALIZED FREQUENCY
0
20
40
60
80
100

TEN POLE HYBRID RIMO FILTER



normalized pole locations

P1	100.000	j0.000
P2	80.902	j58.779
P3	80.902	-j58.779
P4	30.902	j95.106
P5	30.902	-j95.106
P6	94.700	j0.000
P7	99.000	j30.300
P8	99.000	-j30.300
P9	158.000	j105.500
P10	158.000	-j105.500

INITIAL VALUES FOR PROGRAM CONTROL VARIABLES

NF.. 5

NV 5

I 0

NI 0

MOOD 0

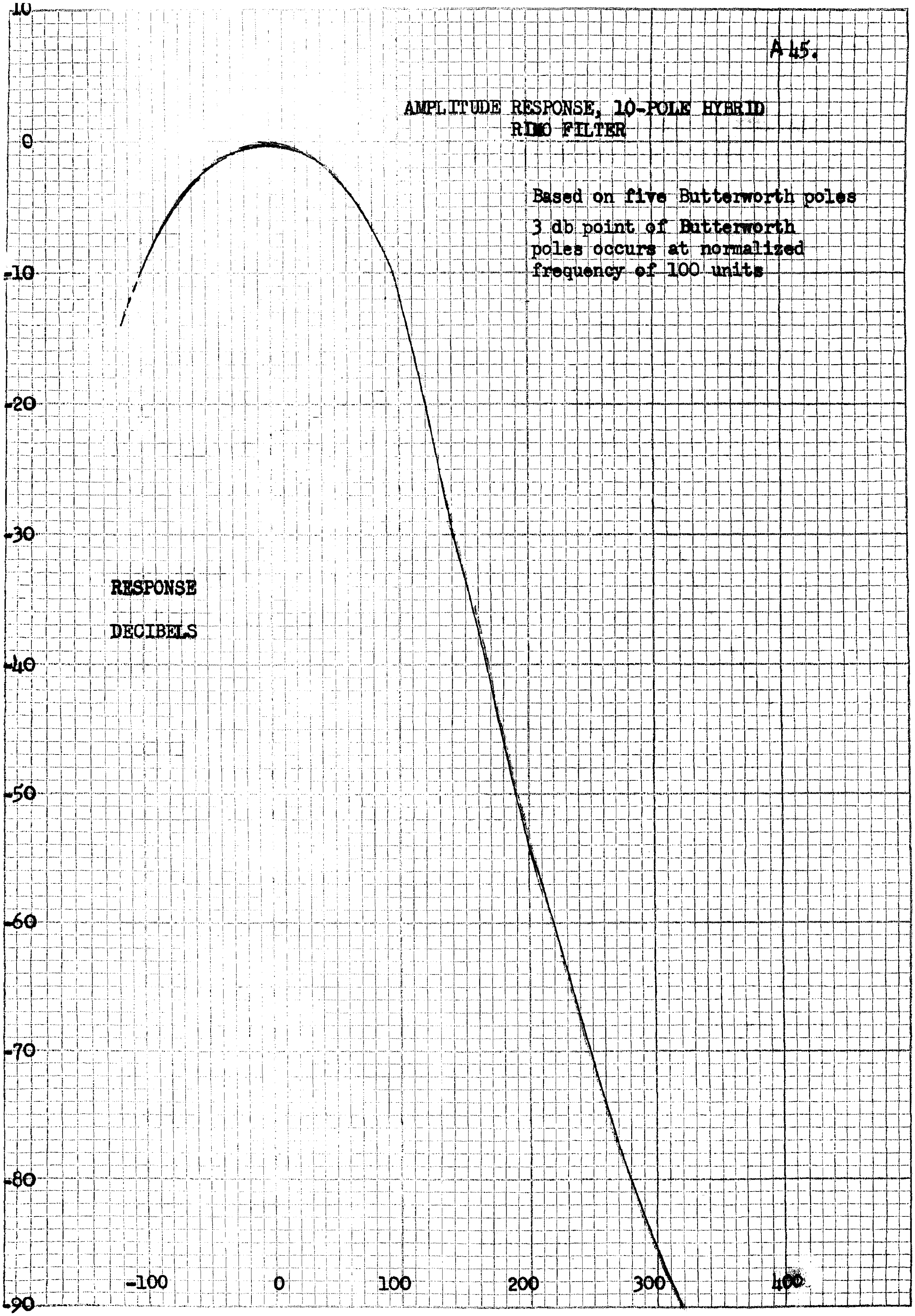
DELL 2.7

COW .... 0.

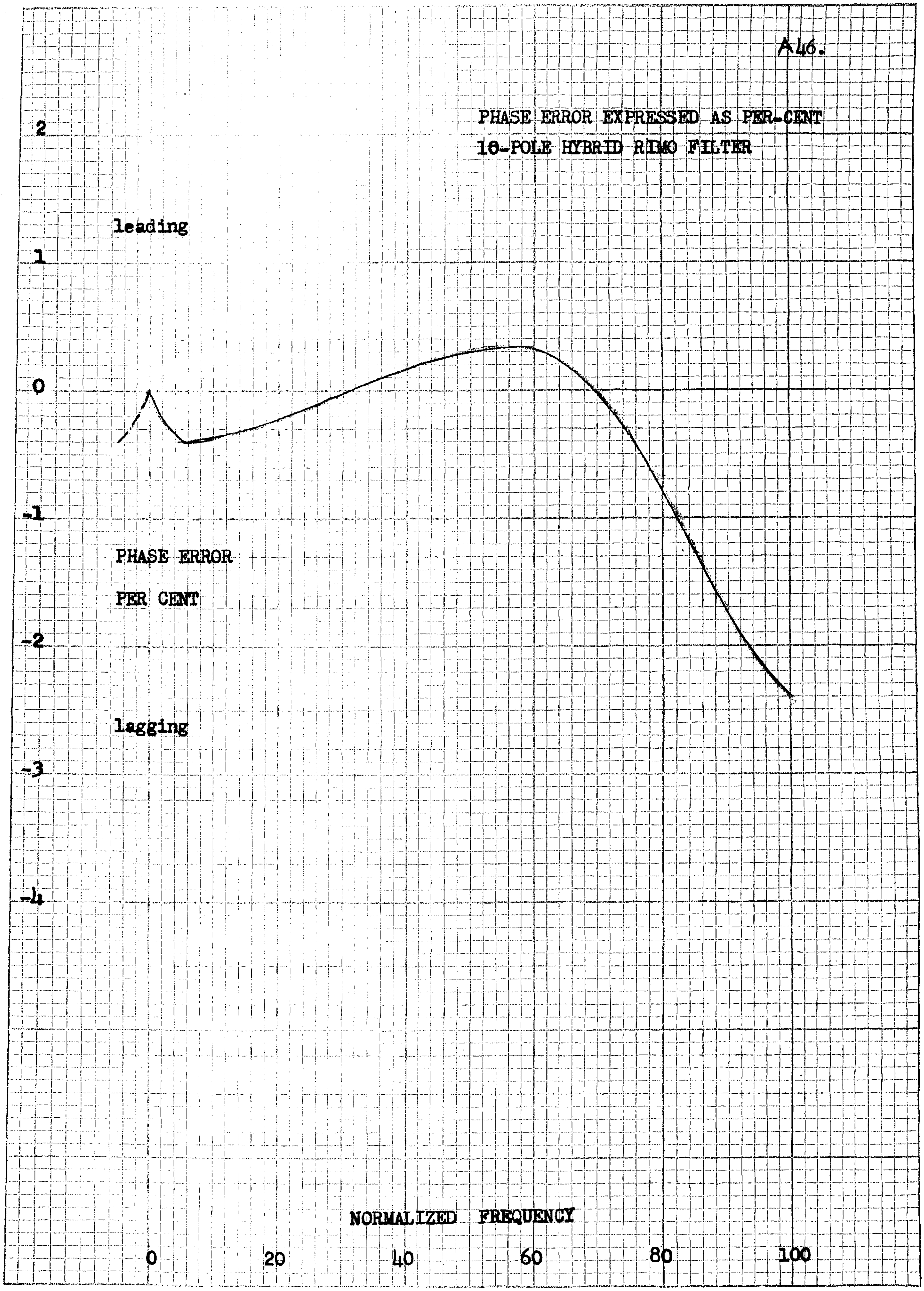
MOO 0

FB... 110.

CONST.. 1.0



A 45.
AMPLITUDE RESPONSE, 10-POLE HYBRID
RIDO FILTER
Based on five Butterworth poles
3 db point of Butterworth poles occurs at normalized frequency of 100 units
RESPONSE
DECIBELS
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
0
100
200
300
400


PHASE ERROR EXPRESSED AS PER-CENT
10-POLE HYBRID RIMO FILTER
2
leading
1
0
-1
PHASE ERROR
PER CENT
-2
lagging
-3
-4
NORMALIZED FREQUENCY
0
20
40
60
80
100

ACKNOWLEDGEMENTS

The work presented in this paper is not entirely that of this writer. Invaluable help has come from various persons associated with the author in his work at BlonderTongue Laboratories, and it must needs be that their assistance and cooperation be here recorded. From Mr. B.H. Tongue and Mr. J.B. Glaab have come ideas and suggestions that have been useful in realizing the IF amplifier. Mr. I. Horowitz offered the 6BA7 mixer as a means to reduce spurious responses.

All the photographs used in the paper were taken by Mr. J.B. Glaab, who also did the developing and printing. The schematic of the tuner was drawn by Mr. C.J. Majko.

The typing of the copies was done by Mrs. C. Brienza, and the copies of the program flow chart were done by Miss L. Kruglow.

Finally, co-credit for the discovery of the Rimo filter must go to the writer's thesis advisor, Prof. R.H. Rose. It was he who thought of the computer-generated universal Rimo filter, amplifying upon the original idea of merely generating a single set of poles to design one IF amplifier; this investigator being just another in a long history of human endevor to see a tree but not the forest.