COMPUTER ANALYSIS OF SFERIC WAVEFORMS

By

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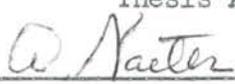
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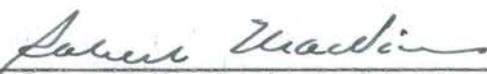
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PREFACE

The purpose of this thesis is to analyze the sferic waveform
from the standpoint of its frequency spectrum. Further, it is hoped
that through use of the computer program given herein, a large amount
of information can be obtained in the future about sferic frequency
spectra.

The author is indebted to Dr. Herbert L. Jones whose invaluable
help and inspiration has made this dissertation possible. Also the
author wishes to express his gratitude to Don Scouten whose technical
advice contributed much to this thesis, and to Felix J. Boudreaux
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To my typist, Miss Barbara Benes, thanks for her untiring efforts.

Last of all, to my wife, Ruby, appreciation is given for her
patience and sacrifice, without which this thesis would not have been
possible.

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CHAPTER I

INTRODUCTION

In 1950 the Jones-Hess high frequency atmospheric was discovered and proved to be directly associated with severe thunderstorms. /Jones-Hess 1952/ Subsequently in 1954 a laborious hand crank study was made of atmospheric waveforms by Joe Pat Lindsey. The method used was to select representative waveforms and then to analyize these selected few using the Fourier Integral and a curve fitting process using (sin x)/x functions. From this analysis it was shown that ordinary thunderstorms, having mostly cloud-to-ground lightning strokes have a frequency spectrum which peaks below 30 kc. As the thunderstorm becomes more severe, possibly culminating in a tornado, the frequency spectrum peak tends to shift upward and a very sharp peak occurs at 150 kc. As a result of the discovery of the 150 kc. peak, a 150 kc. static direction finder was developed at Oklahoma State University and constructed by R. D. Kelly in 1955. Use of the 150 kc. static direction finder resulted in the discovery of an inter cloud discharge which was named the "Tornado Oscillator" by Dr. H. L. Jones of Oklahoma State University. Studies using the 150 kc. static direction finder led to the discovery that the "Tornado Oscillator", when a tornado was eminent, had a discharge rate of 15 to 20 per second, 30 to 90 minutes prior to formation of the tornado funnel. /Kelly 1957/

The discoveries made to date, as delineated above, are extremely

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satisfying; however, two facts are very apparent when a critical eye is turned on the research. First Mr. Lindsey was working under a decided handicap in analyzing waveforms by the hand crank method in that only a few analyses were possible due to the extremely long time required for each analysis. Secondly the waveform receiver used had an upper frequency limit of about 200 kc.

A spectrial analysis of many multi-spheric waveforms then, considering the valuable information Mr. Lindsey gained from analyzing a few, should yield a great amount of information as to the types of thunderstorms and severe weather associated with certain types of sferic waveforms. This analysis is the prime objective of this thesis. The analysis will be accomplished through use of an IBM 650 computer, programmed to use the Fourier Integral to determine the frequency spectrum of sferic waveforms.

The static interference encountered during severe thunderstorms on ordinary radio receivers indicates that a considerable amount of sferic energy is propagated at 550 kc. to 1600 kc. The almost complete absence of static interference on television receivers indicates, however, that no great amount of sferic energy is propagated at these higher frequencies. Therefore, a Tektronic 531 oscilloscope and the Q-3 will be used as sferic receivers in order that higher sferic frequency components may be calculated.

Thus both of Mr. Lindsey's handicaps will be removed and a great deal of information about the frequency spectrum of sferics can be obtained. A study of this type should properly be continued over a period of many years and many thunderstorms, whereas the study herein contained covers only a few months and a few thunderstorms. Hence this dissertation may provide a future useful tool for probing one of nature's

many secrets, the severe thunderstorm lightning discharge.

CHAPTER II

THE FOURIER INTEGRAL

A development of the Fourier integral from the Fourier series will be presented in this chapter. It will not be rigorous, but for the evaluations at hand the development will be sufficient.

FOURIER'S THEOREM. If a function $f(t)$ of t has a finite number of points of ordinary discontinuity and a finite number of maxima and minima in the interval $0 \leq t \leq 2\pi$, and if the function be arbitrarily defined within this interval and defined by the relation

$$f(t + 2\pi) = f(t) \tag{2-1}$$

for values of t outside this interval, then

$$f(t) = a_0/2 + \sum_1^\infty (a_n \cos nwt + b_n \sin nwt) \tag{2-2}$$

where

$$a_0 = 1/\pi \int_0^{2\pi} f(t) \, dt$$

$$a_n = 1/\pi \int_0^{2\pi} f(t) \cos nwt \, dt \tag{2-3}$$

$$b_n = 1/\pi \int_0^{2\pi} f(t) \sin nwt \, dt$$

The equations (2-3) are termed the Cauchy integrals after their orginator. The proof of these integral formulas will not be given here.[1]

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[1]R. G. Manley, <u>Waveform Analysis</u>, John Wiley and Sons Inc. (New York, 1945), pp. 144-147.

It is possible, and indeed necessary, to write the Fourier series in other forms. Two of these are given below. Consider the series

$$f(t) = S = A_0 + \sum_{1}^{\infty} (a_n \cos nwt + b_n \sin nwt) \qquad (2\text{-}4)$$

since

$$\cos nwt = \frac{e^{jnwt} + e^{-jnwt}}{2} \qquad (2\text{-}5a)$$

and

$$\sin nwt = \frac{e^{jnwt} - e^{-jnwt}}{2j} \qquad (2\text{-}5b)$$

the summation quantity, equation (2-4), becomes

$$a_n \frac{(e^{jnwt} + e^{-jnwt})}{2} + b_n \frac{(e^{jnwt} - e^{-jnwt})}{2j} \qquad (2\text{-}6)$$

expanding and rearranging terms gives

$$\frac{(a_n - jb_n)}{2} e^{jnwt} + \frac{(a_n + jb_n)}{2} e^{-jnwt} \qquad (2\text{-}7)$$

hence the series S is given by

$$S = \sum_{0}^{\infty} C_n e^{jnwt} + D_n e^{-jnwt} \qquad (2\text{-}8)$$

It is readily observed that the second term of the summation may be represented by

$$\sum_{0}^{-\infty} D_n e^{jnwt} \qquad (2\text{-}9)$$

hence the series may be written as

$$S = \sum_{-\infty}^{+\infty} B_n e^{jnwt} \qquad (2\text{-}10)$$

where

$$B_{+n} = 1/2 \ (a_n - jb_n)$$

$$B_{-n} = 1/2 \ (a_n + jb_n) \qquad (2\text{-}11)$$

$$B_o = A_o$$

The determination of the value of the constants in (2-7) will be of importance in a later development, hence the method is presented here. Making use of the Cauchy integrals, we obtain:

$$\frac{a_n \pm b_n}{2} = 1/2\pi \int_0^{2\pi} f(t) \cos wt \pm j \, f(t) \sin wt \, dt \qquad (2\text{-}12)$$

which after conversion and collection of terms reduces to

$$1/2\pi \int_0^{2\pi} f(t) e^{\pm jwt} \, dt. \qquad (2\text{-}13)$$

To proceed from the Fourier series to the Fourier integral we begin with equation (2-11) and, writing it in a more general form, have

$$f(t) = \sum_{-\infty}^{\pm\infty} B_n e^{jnw_o t} \qquad (2\text{-}14)$$

where

$$B_n = 1/T \int_{-T/2}^{+T/2} f(t) e^{-jnw_o t} \, dt. \qquad (2\text{-}15)$$

Now consider: if $nw_o = w$ /which implies any frequency f/ then $\Delta nw_o = w$ /which implies any incremental frequency f/ hence let $\Delta n = 1$ then

$$f(t) = \sum_{-\infty}^{\pm\infty} \frac{B_n}{w_o} e^{jnw_o t} \ (\Delta nw_o) \qquad (2\text{-}16)$$

and therefore

$$B_n/w_o = g(w) = 1/2\pi \int_{-T/2}^{+T/2} f(t) e^{-jw_o t} \, dt. \qquad (2\text{-}17)$$

Observe that the Limit $1/T$ = Limit $w_o/2\pi$ = 0
$\qquad\qquad T \to \pm\infty \qquad T \to \pm\infty$

and also in the limit $\Delta nw_0 = dw$ and $nw_0 = w$. Therefore the spacing between harmonics approaches zero and g(w) becomes a continuous function of frequency. The Fourier series then becomes the Fourier integral

$$f(t) = \int_{-\infty}^{+\infty} g(w)e^{jwt}\, dt \qquad (2\text{-}18)$$

where

$$g(w) = 1/2\pi \int_{-\infty}^{+\infty} f(t)e^{-jwt}\, dt \qquad (2\text{-}19)$$

The two expressions, (2-18) and (2-19), are the exponential forms of the Fourier integral. Close observation reveals that (2-19) will convert any function of time, f(t), to its frequency function, g(w). Similarly (2-18) will change any frequency function, g(w), to its corresponding function of time, f(t). Restrictions such as the finiteness of the integral of f(t) dt to allow for convergence, a finite number of maxima and minima, and a finite number of points of discontinuity apply here in a manner similar to Fourier series restrictions. For the problem at hand, however, all these boundary conditions are met.

Another form of the Fourier integral is of interest here, hence the development is given. Since from equation (2-19)

$$g(w) = 1/2\pi \int_{-\infty}^{+\infty} f(t)(\cos wt - j\sin wt)\, dt \qquad (2\text{-}20)$$

let

$$g(w) = 1/2(a_w - jb_w). \qquad (2\text{-}21)$$

Equating like parts on the right of equations (2-20) and (2-21) gives

$$a(w) = 1/\pi \int_{-\infty}^{+\infty} f(t)\cos wt\, dt \qquad (2\text{-}22)$$

$$b(w) = 1/\pi \int_{-\infty}^{+\infty} f(t)\sin wt\, dt \qquad (2\text{-}23)$$

where a(w) is an even function since f (t) = f (-t) and b (w) is an odd function since f (t) = -f (-t). Applying the above reasoning and equations to (2-18) we have

$$f\ (t)\ =\ 1/2\ \int_{-\infty}^{+\infty} a\ (w)\ \cos\ wt\ +\ b\ (w)\ \sin\ wt\ +\ j\ \underline{/}a\ (w)\ \sin\ wt\ -$$

$$b\ (w)\ \cos\ wt\_\underline{/}\ dw. \hspace{2cm} (2\text{-}24)$$

Since the imaginary part of the integral is an odd function its value is zero. The real part is an even function and not zero. Hence the integral reduces to the real part alone and is integrated from 0 to +∞ only. Equation (2-24) is easily reduced to the required form. Let

$$c\ (w)\ =\ \underline{/}a\ (w)^2\ +\ b\ (w)^2\_\underline{/}^{1/2} \hspace{2cm} (2\text{-}25)$$

and

$$\theta\ =\ \tan^{-1}\ a\ (w)/b\ (w) \hspace{2cm} (2\text{-}26)$$

then

$$f\ (t)\ =\ \int_{0}^{+\infty} c\ (w)\ \cos\ (wt\ +\ \theta)\ dw \hspace{2cm} (2\text{-}27)$$

where c (w) is the amplitude function and $\theta(w)$ is the phase shift function.

Considering then equation (2-25), if the values of c (w) are calculated for incremental frequencies and then plotted as ordinate against abscissa of frequency, a frequency spectrum plot will result. This procedure is the final objective of this dissertation, to obtain and analyze frequency spectrum plots of sferic waveforms. It should be observed here that c (w) is directly proportional to sferic electric field strength. As a secondary objective, then, field strength may be calculated.

The tool for analyzing sferic waveforms has been developed and will now be put to use. As with any tool, instructions for its proper use are

needed, and the Fourier integral is no exception. Consider then equation (2-25) which consists of three parts; c (w), a (w), and b (w). The values of a (w) and b (w) are given in equations (2-22) and (2-23). It is therefore these two equations that must first be evaluated before determining c (w), the final desired result.

Since the function f (t) is nonanalytic, a (w) and b (w) must be determined nonanalytically. The method is to assume that f (w) is linear between two points, t' and t", arbitrarily close together. The problem then reduces to obtaining the several Δ a (w) and Δ b (w) and summing to obtain the total value. The equation for f (t), between t' and t" may be obtained through use of the point slope equation of a straight line

$$(f - f') = M (t - t') \qquad (2\text{-}29)$$

where

$$M = \frac{f'' - f'}{t'' - t'} \qquad (2\text{-}30)$$

Therefore the equation for a (w) is

$$a (w) = \int_{-\infty}^{+\infty} \cos wt \left[f' + \frac{f'' - f'}{t'' - t'} (t - t') \right] dt \qquad (2\text{-}31)$$

which readily reduces to

$$\sum \frac{f'' - f'}{t'' - t'} \frac{1}{w^2} (\cos wt'' - \cos wt') + \frac{f'' \sin wt'' - f' \sin wt'}{w} \qquad (2\text{-}32)$$

Considering the two terms of equation (2-32), the first term is composed of cosine terms, hence it is an even function and not equal to zero. The second term, however, is composed of sine terms, and is an odd function and therefore is equal to zero. The value of a (w) then reduces to that of only the first term. Therefore

$$a (w) = \sum \frac{\Delta f}{\Delta t} \frac{1}{w^2} \Delta \cos wt. \qquad (2\text{-}33)$$

Following a similar procedure, b (w) is easily shown to be

$$b\ (w) = \sum \frac{\Delta\ f}{\Delta\ t}\ \frac{1}{w^2}\ \Delta \sin wt \qquad (2\text{-}34)$$

Once a given set of a (w) and b (w) are determined, the next step is to determine the particular c (w) using equation (2-25).

To summarize, then, we must do the following in the order given.

(1.)   Determine Δ t for the particular waveform to be analyzed.

(2.)   Determine f values, the length of each ordinate for each t value.

(3.)   Perform the evaluation (2-33) to determine a (w).

(4.)   Perform the evaluation (2-34) to determine b (w).

(5.)   Perform the evaluation (2-25) to determine c (w).

(6.)   Repeat steps 3, 4, and 5 for as many (w) as desired.

(7.)   Plot the various c (w) from step 5 as a function of (w).

(8.)   Make an analysis of the frequency spectrum plot of step 7.

For step (1), Δ t is arbitrarily chosen but will usually be 1mm. Larger intervals for Δ t may be used if the waveform is very smooth and linear over any interval. In step (2) f values are, of course, determined directly from the choice of Δ t. Steps (3), (4), (5), and (6) are performed by the IBM 650 computer using the program given in Chapter III. Steps (7) and (8) are then performed manually to complete the analysis.

CHAPTER III

THE PROGRAM

For a long experienced computer programmer, the IBM 650 SOAP
program might very well read like a book. However, a compute diagram
and explanation are extremely helpful; and indeed for most readers will
be indispensable. The diagram is drawn in extreme detail outlining every
computed quantity. Further, the numbers in parenthesis following each
step indicate the instructions in the program which perform the given
step.

The Compute Diagram

(1.) Load data, first t then f values (22-37).

(2.) t" - t' ----------- store -- loop to compute all (t" - t').

(3.) f" - f' (40-42).

(4.) M = $\Delta f/\Delta t$ ------- store -- loop to compute all M (43-46).

(5.) w ------------------ store (47-51).

(6.) w^2 ------------------ store (52-53).

(7.) M/w^2 --------------- store (54-57).

(8.) wt" --------------- store (58-60).

(9.) cos wt" = cos B --- store (61-62).

(10.) M/w^2(cos wt" - cos wt') = delta a(w) -- store (63-66).

(11.) sin wt" = sin B --- store (67-69).

(12.) M/w^2(sin wt" - sin wt') = delta b(w) -- store (70-73).

(13.) cos wt" and sin wt" shift location (74-77).

(14.) Loop to compute a(w) and b(w) (78-81).

(15.) $\underline{/b}\ (w)\underline{\ /}^2$ ----------- store (82-84).

(16.) $\underline{/a}\ (w)\underline{\ /}^2$ (85-86).

(17.) $\underline{/b}\ (w)\underline{\ /}^2 + \underline{/a}\ (w)\underline{\ /}^2$ (87).

(18.) c (w) $= \left\{ \underline{/b}\ (w)\underline{\ /}^2 + \underline{/a}\ (w)\underline{\ /}^2 \right\}^{1/2}$ --- store for pcha (88-89).

(19.) Reset storage boxes a (w), b (w), cos, and sin (90-95).

(20.) Step pchb storage (96-98).

(21.) Test for pcha (99-100).

    A. NO return to Wone.

    B. YES

        1. Pcha (101).

        2. Reset pchb storage instruction (102-103).

        3. Test for upper frequency limit (104-105).

           Loop if not through (106).

           Read in new data if through (106).

Program Description

The program has two limitations that keep it from being entirely general in nature. First t" - t' is always a constant, therefore, the t" - t' step shown in the compute diagram is not in the program. Second, the separation of frequency, where c (w) is computed, is always constant. The program is, however, sent to locations 9010 and 9013 at the proper time in order that these limitations may be canceled if desired. Core storage locations are used as storage for intermediate computed results, various constants which are used often, and control card contents. The program is listed in SOAP and machine language, because it is felt that

these listings together are more easily read and if necessary altered.
One word of caution is in order. The program is written for use on an
IBM 650 with Indexing Registers A, B, and C, Immediate Access Storage
with sixty words, and Floating Decimal Arithmetic Operation. The num-
bered subparagraphs which follow are further descriptions of the program.

(1.) Two hundred drum locations each are reserved for t, f, and m
storage. However f storage locations 1200 to 1399 may be used for m
storage if desired, provided that the f values are used only once to com-
pute delta-f. Instruction DFTH is altered to read STU F0001 A to do this.

(2.) Drum locations 0700 to 0770 are initially reserved for a trace
routine and hence may be used for other purposes after program debugging
is accomplished.

(3.) All t values are listed in terms of time in seconds and not mm.
or inches. Delta-t, however, is in the same units as f.

(4.) Control card contents are as follows:

> Word 1 NOP 0000 RDT ---- Second instruction of the program.
>
> Word 2 FREQ ------------- Starting frequency - CFIV.
>
> Word 3 CFIV ------------- Incremental stepping frequency.
>
> Word 4 CSEV ------------- Highest frequency for which c (w) is
> to be computed.
>
> Word 5 ----------------- Waveform order number.
>
> Word 6 DELT ------------- Delta-t in floating point form.
>
> Word 7 CFOU ------------- Number of ordinates - 2 = 00 0000 XXXX.
>
> Word 8 CTWO ------------- Number of abscissa = 00 0000 XXXX.

The control card contents are read into and stored in locations 9000
through 9007. Also note that the control card must be a load card.

(5.) In recording waveform ordinates for computation, the following
are recorded on each recording sheet:

A. Date.

B. Time in 24 hour clock notation and an indication whether time is local or (z) time.

C. Waveform number. This is the identification word that will be in the program to associate all data with its respective waveforms and will be assigned in simple chronological order.

(6.) All symbolic addresses consist of four and only four letters.

(7.) Data card contents are as follows:

Word 1 -- 27 9035 XXXX --- Col. 1 - 10.

Word 2 to Word 6 -- Data in floating point form Col. 11 - 60.

Word 7 -- Card number in chronological order of the particular data being loaded -- Col. 61 - 70.

Word 8 -- Data number from 5-C -- Col. 71 - 80.

Note that all data cards must be load cards.

(8.) Loading orders for three possible cases are listed below:

A. Initial loading order.

1. Clearing routine.

2. Sub-routine deck.

3. Program in one word load form.

4. Transfer card to SART.

5. Control card.

6. Data, t values followed by f values.

B. For second or Nth data; after number 8-A-6 put:

1. Transfer card to SART.

2. Control card.

3. Data, t values then f values.

C. For different computation on same data; after number

8-A-6 put:

1. Transfer card to NEXH.

2. Control card with word 1 changed to NOP 0000 WONE.

	REG	T1000	1199		2				
	REG	F1200	1399		3				
	REG	M1400	1599		4				
	REG	P1627	1634		5				
	REG	0300	0499		6				
	REG	0450	0599		7				
	REG	0700	0770		8				
	EQU	CONE	9025		9				
	EQU	CTWO	9007		10				
	EQU	CTHR	9027		11				
	EQU	CFOU	9006		12				
	FQU	CFIV	9002		13				
	EQU	CSIX	9028		14				
	EQU	CSEV	9003		15				
	EQU	CTPI	9030		16				
	EQU	FREQ	9001		17				
	EQU	DELT	9005		18				
	EQU	IDW	9004		19				
SART	RD1	9000	9000		20	0050	70	9000	9000
9000	NOP	0000	RDT		21	9000	00	0000	0004
RDT	RAA	0000	RDTA	LOADT	22	0004	80	0000	0060
RDTA	RD1	9034	9034		23	0060	70	9034	9034
9034	SET	9035			24	9034	27	9035	0015
	SIB	T0001	A		25	0015	28	3000	0012
	AXA	0005			26	0012	50	0005	0018
	SXA	CTWO			27	0018	51	9007	0026
	BMA	NEXE	NEXF		28	0026	41	0029	0030
NEXE	AXA	CTWO	RDTA		29	0029	50	9007	0060
NEXF	RAA	0000	RDF	LOADF	30	0030	80	0000	0036

```
RDF       RD1  9034      9034                      31  0036    70  9034  9034
   9034   SET  9035                                32  9034    27  9035  0041
          SIB  F0001 A                             33  0041  · 28  3200  0062
          AXA  0005                                34  0062    50  0005  0068
          SXA  CTWO                                35  0068    51  9007  0076
          BMA  NEXG      NEXH                       36  0076    41  0079  0080
NEXG      AXA  CTWO      RDF                        37  0079    50  9007  0036
NEXH      LDD  IDW                                 38  0080    69  9004  0086
          STD  P0008                               39  0086    24  1634  0037
          RAA  CFOU      DELF      DELTAF           40  0037    80  9006  0045
DELF      RAU  F0002 A                             41  0045    60  3201  0055
          FSB  F0001 A   9010                       42  0055    33  3200  9010
DFTW      FDV  DELT      DFTH      SLOPEM           43  0100    34  9005  0003
DFTH      STU  M0001 A                             44  0003    21  3400  0053
          SXA  0001                                45  0053    51  0001  0009
          BMA  WONE      DELF                       46  0009    41  0112  0045
WONE      RAU  FREQ                OMEGA            47  0112    60  9001  0019
          FAD  CFIV                                48  0019    32  9002  0049
          STU  FREQ                                49  0049    21  9001  0007
          FMP  CTPI                                50  0007    39  9030  0110
          STU  9011                                51  0110    21  9011  0017
          FMP  9011                OMEGASQ          52  0017    39  9011  0020
          STU  9012      9013                       53  0020    21  9012  9013
ZRAC      RAC  0000      SLPE      MOVERWSQ         54  0150    88  0000  0006
SLPE      RAU  M0001 C                             55  0006    60  7400  0105
          FDV  9012                                56  0105    34  9012  0008
          STU  9014      TPRI                       57  0008    21  9014  0065
TPRI      RAU  T0002 C             WT               58  0065    60  7001  0155
          FMP  9011                                59  0155    39  9011  0058
```

Label	Op	A	B	Comment					
	STU	9018			60	0058	21	9018	0115
	LDD	COSB	0350	COSWT	61	0115	69	0118	0350
COSB	STU	9019			62	0118	21	9019	0025
	FSB	9016		DELTAAW	63	0025	33	9016	0205
	FMP	9014			64	0205	39	9014	0108
	FAD	9020			65	0108	32	9020	0087
	STU	9020			66	0087	21	9020	0095
	RAU	9018		SINWT	67	0095	60	9018	0103
	LDD	SINB	0300		68	0103	69	0056	0300
SINB	STU	9021			69	0056	21	9021	0013
	FSB	9017		DELTABW	70	0013	33	9017	0043
	FMP	9014			71	0043	39	9014	0046
	FAD	9022			72	0046	32	9022	0075
	STU	9022			73	0075	21	9022	0033
	LDD	9019		SHIFTCOS	74	0033	69	9019	0039
	STD	9016			75	0039	24	9016	0145
	LDD	9021		SHIFTSIN	76	0145	69	9021	0001
	STD	9017			77	0001	24	9017	0057
	AXC	0001		TEST	78	0057	58	0001	0063
	SXC	CFOU			79	0063	59	9006	0021
	BMC	NEXA	NEXB	LOOP	80	0021	49	0024	0125
NEXA	AXC	CFOU	SLPE		81	0024	58	9006	0006
NEXB	RAU	9022		BWSQ	82	0125	60	9022	0083
	FMP	9022			83	0083	39	9022	0136
	STU	9023			84	0136	21	9023	0093
	RAU	9020		AWSQ	85	0093	60	9020	0051
	FMP	9020			86	0051	39	9020	0054
	FAD	9023		BWPLUSAW	87	0054	32	9023	0133
	RAC	NEXC	0500	CW	88	0133	88	0183	0500

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NEXC	STU	P0001	PCHB			89	0183	21	1627	0130
PCHB	SUP	8001		RESET		90	0130	11	8001	0137
	STU	9020				91	0137	21	9020	0195
	STU	9022				92	0195	21	9022	0153
	STU	9017				93	0153	21	9017	0011
	LDD	CTHR				94	0011	69	9027	0067
	STD	9016				95	0067	24	9016	0023
	RAU	NEXC		STEPPCH		96	0023	60	0183	0187
	AUP	CONE				97	0187	10	9025	0245
	STU	NEXC				98	0245	21	0183	0186
	SUP	CSIX		TEST		99	0186	11	9028	0143
	NZU	WONE	PCHA	LOOP		100	0143	44	0112	0048
PCHA	PCH	P0001		PCHOUT		101	0048	71	1627	0027
	LDD	9024		RESET		102	0027	69	9024	0233
	STD	NEXC				103	0233	24	0183	0236
	RAU	FREQ		TEST		104	0236	60	9001	0193
	FSB	CSEV				105	0193	33	9003	0073
	BMI	WONE	8000	LOOP		106	0073	46	0112	8000
CONE	00	0001	0000			107	9025	00	0001	0000
CTHR	10	0000	0051			108	9027	10	0000	0051
CSIX	STU	P0008	PCHB			109	9028	21	1634	0130
CTPI	62	8318	5351			110	9030	62	8318	5351
9010	00	0000	DFTW	DELTNTKNST		111	9010	00	0000	0100
9011	00	0000	0000	WSTR		112	9011	00	0000	0000
9012	00	0000	0000	WSQSTR		113	9012	00	0000	0000
9013	00	0000	ZRAC	DELFNTKNST		114	9013	00	0000	0150
9014	00	0000	0000	MOVERWSQST		115	9014	00	0000	0000
9016	10	0000	0051	COSASTR		116	9016	10	0000	0051
9017	00	0000	0000	SINASTR		117	9017	00	0000	0000

9018	00	0000	0000	WTSTR	118	9018	00	0000	0000
9019	00	0000	0000	COSBSTR	119	9019	00	0000	0000
9020	00	0000	0000	AWSTR	120	9020	00	0000	0000
9021	00	0000	0000	SINBSTR	121	9021	00	0000	0000
9022	00	0000	0000	BWSTR	122	9022	00	0000	0000
9023	00	0000	0000	BWSQSTR	123	9023	00	0000	0000
9024	STU	P0001	FCHB	RESTORINST	124	9024	21	1627	0130

CHAPTER IV

WAVEFORM COLLECTION AND ANALYSIS

The Fourier Integral of Chapter II and the program for evaluating

the integral from Chapter III will be set to use in this chapter to

obtain frequency spectra of sferic waveforms. The method of collecting

the data, processing it, and readying it for analysis by the computer

will be discussed. A theory of sferic waveforms is set forth and the

handling of the computed output data is described.

Collection of Data

Sferic waveforms, as is well known, are electromagnetic radiations

resulting from lightning discharges. To collect a sampling of this

radiation there need be erected an antenna for detecting the signal, a

receiver and display unit to receive, amplify, and display the signal,

and a recording device for making a permanent record. For this thesis

two pieces of equipment were used for receiver and display units: a

Q-3 sferic unit and a Tektronic Oscilloscope. The whip antenna of the

Q-3 is used for detecting the sferic signals. Two modified Dumont 321-A

oscilloscope cameras are used to permanently and simultaneously record

the displayed sferic waveform on 35 mm. film. Diagrams of the necessary

wiring and connections are given in Figures 4.1 and 4.2. The diagrams

are the ultimate in simplification; however, complete detailed descrip-

tion of all the equipment shown may be found in the respective equipment
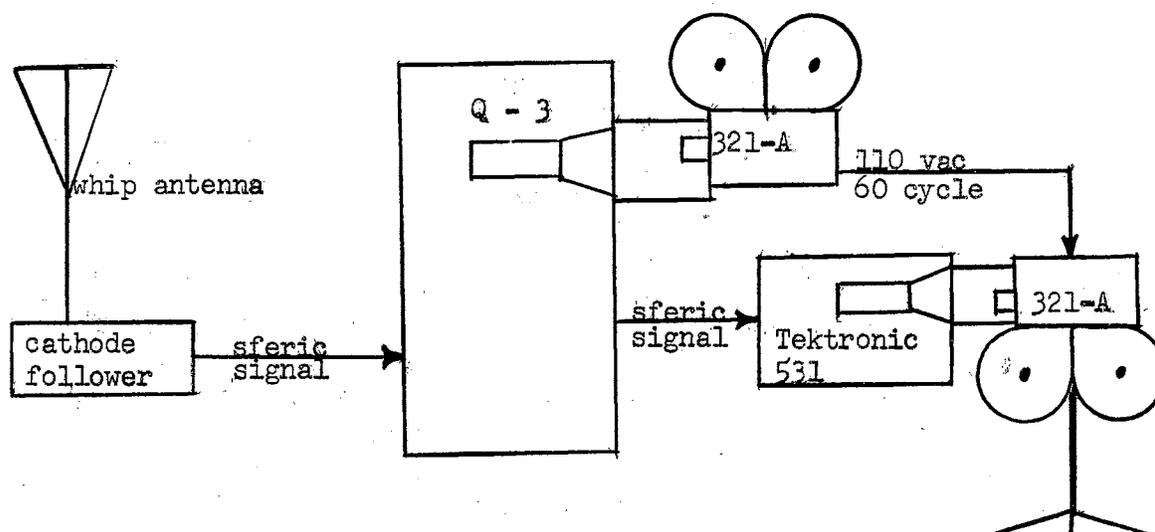
Figure 4.1. Block Diagram

NE51 timing light inside tektronic viewing
housing. Provides 1 and 6 sec. timing flashes.

Flasher J-5203
to Ind. J-2403

J-5202-2

A to C
Short circuit

NE51 inside lightbox on
unit 2400

100 k
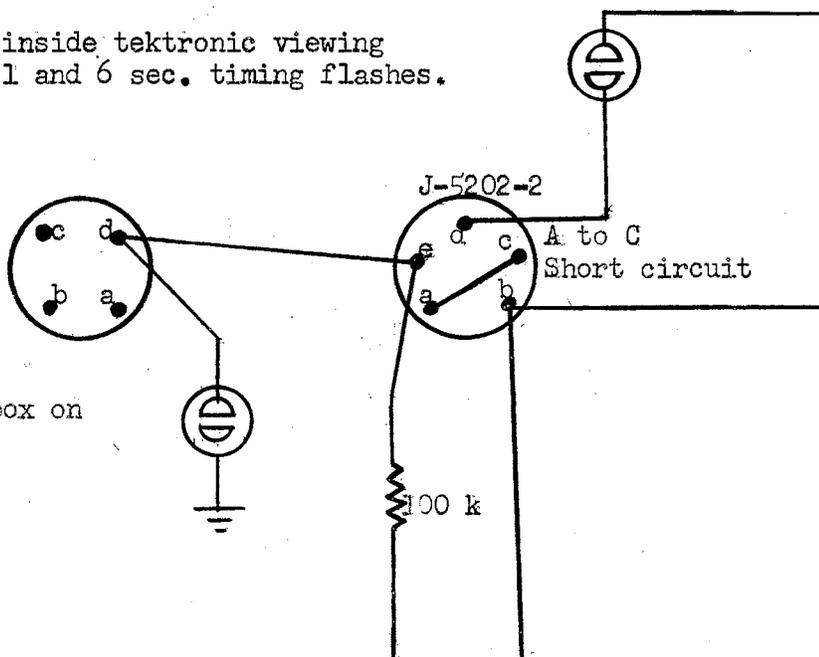
From tektronic camera motor
on light indicator circuit.
Provides 110 vac 60 cycle
signal when motor is
running.

Figure 4.2. Wiring Diagram

manuals. Once the camera film is exposed, it is a relatively simple process to develop and dry the film and roll it onto rolls ready for waveform analysis on the viewer.

Selection of Waveforms

In selecting waveforms to be analyzed it was decided to scan the film records to ascertain if there were recurring types of waveforms. Recurring types were found, and it was decided to analyze one of these; thus classifying one type of sferic activity.

The film records from the very active storm of June 11, 1959 were used for analysis. This storm developed east of the Tornado Laboratory and moved slowly in a westerly direction toward Stillwater. Three-minute film records were made at 2050, 2105, 2135, 2205, and 2235. Thirty-second recordings were made at 2250, 2255, 2300, 2305, 2310, and 2315. A final three-minute recording was made at 2335. During the thirty-second recordings made every five minutes, the storm was directly overhead. This small amount of data, only three minutes in length, proved to be some of the best data recorded at the Laboratory. The film speed used was 200 feet per minute and a large amount of clear, usable data was obtained. Several of the waveforms were traced onto graph sheet tracing paper, and from these tracings, computer data was taken. The procedure is quite simple. The viewer magnification is adjusted so that the time length of the displayed waveform is a rational number of mm., that is, 500 u sec. = 125 mm. or 100 u sec. = 250 mm. The particular waveform is then carefully traced. From the graphical tracing, the t values, f values, and delta-t values are determined and recorded on data paper. The remaining task is to punch the values into data

cards and load the data, along with the program of Chapter III, onto the
computer, which then computes the frequency spectrum amplitudes. From a
listing of the answers, a frequency spectrum plot may be made and from
this conclusions are drawn.

A Sferic Waveform Theory

In viewing the film records many sferic waveforms of the general
type shown in Figure 4.3 were discovered. The writter became interested
in this particular type of waveform for several reasons. First, the 75
kc. and the 150 kc. oscilloscope traces indicated strong excitation when
this type of waveform occurred. Second, the 150 kc. DF trace was very
sharp at these times, indicating a vertically-polarized type of discharge;
that is, a vertical discharge possibly similar to the tornado oscillator
discharge. It is theorized that the first sharp rise of the waveform is
caused by the rapid build up of the discharging current between separated
charges. The discharge results in a vertically-polarized electromagnetic
field. This statement is taken from the well known Lenz's law which
states that an increasing current will cause a magnetic flux or field
which generates an electric field that tends to oppose the change in
current. Further, if the current path is vertical, the magnetic field
will be circular about it in a horizontal plane and the electric field
must be perpendicular to the magnetic field /Figure 4.4a7. The almost
immediate reversal of the waveform sense results from the decay of the
discharge current and the physical laws governing this decay. The current
cannot go to zero immediately; but as it begins to decay, the electric
field can and does reverse, that is, to oppose the change in current
according to Lenz's law /Figure 4.4b7. An exponential decay of the
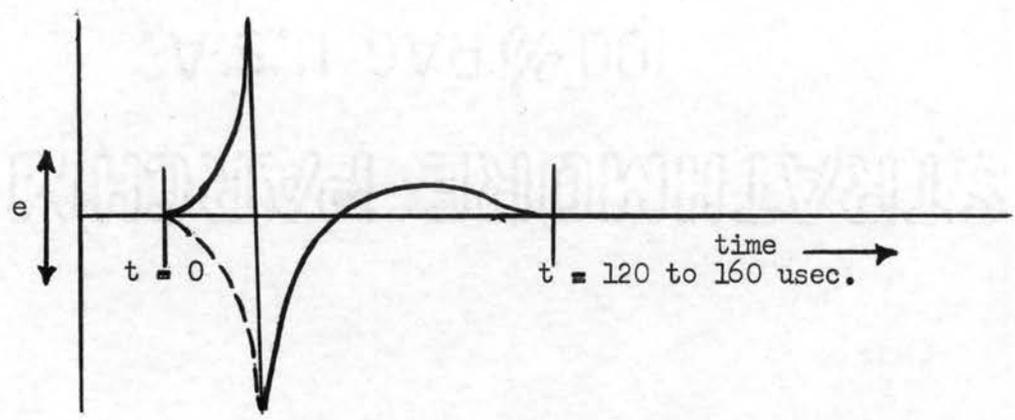
Figure 4.3. Sferic Waveform Example
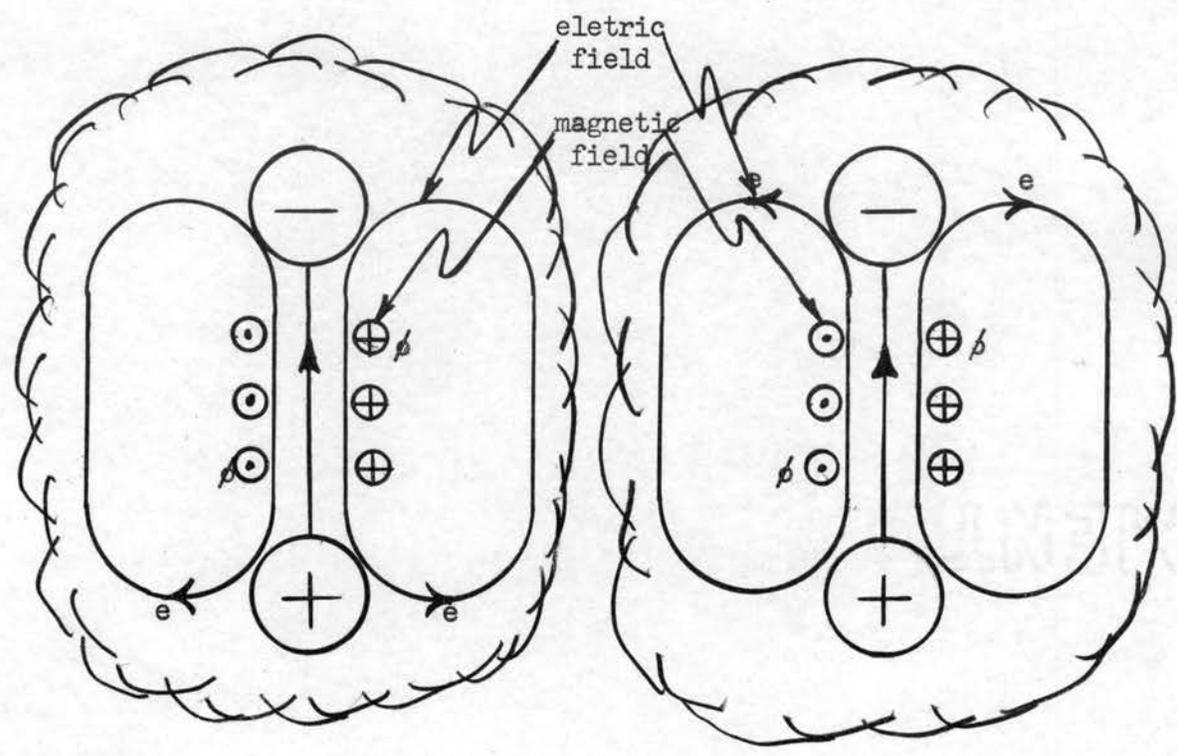
Figure 4.4a. Increasing Current   Figure 4.4b. Decreasing Current

Figure 4.4. Lightning Discharge Diagram

current and the electromagnetic field, with slightly less than critical damping, is the final result. The average value of the discharge current is between 5000 and 30,000 amperes and flows for 100 to 1,000 microseconds. (Boudreaux 1959) This is about as close to an infinite current pulse as will ever be found. Suppose the first sharp rise of the waveform, /Figure 4.3/, is rotated about the time axis. The waveform then approximates the current-time graph of an R-L-C circuit with direct current voltage excitation and having slightly less than critical damping. The waveform shown is of the electric field. However, the electric field waveform must follow, in the reverse sense, the current discharge waveform. It appears, therefore, that the discharge action must parallel the action of an R-L-C circuit with a suddenly applied high level direct current voltage. All of the preceding is based on induction field theory. However, both an induction field and a radiation field are associated with a lightning discharge. It seems highly plausible then that the two fields are closely related, especially since they both result from the same disturbance.
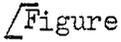
Waveform Spectra

The remainder of this chapter will be devoted to waveforms and their spectrum plots. The eight waveforms and spectra given were selected from among many as being typical of this type. All of the waveform spectra given are observed to have a large amount of low frequency component, that is, below 30 kc. Also evident, however, are relative maximum points above 30 kc. Observations will reveal a relative maximum close to 150 kc. in almost every instance, thus cause of the triggering of the 150 kc. DF trace is established.

time
125 mm. = 500 usec.
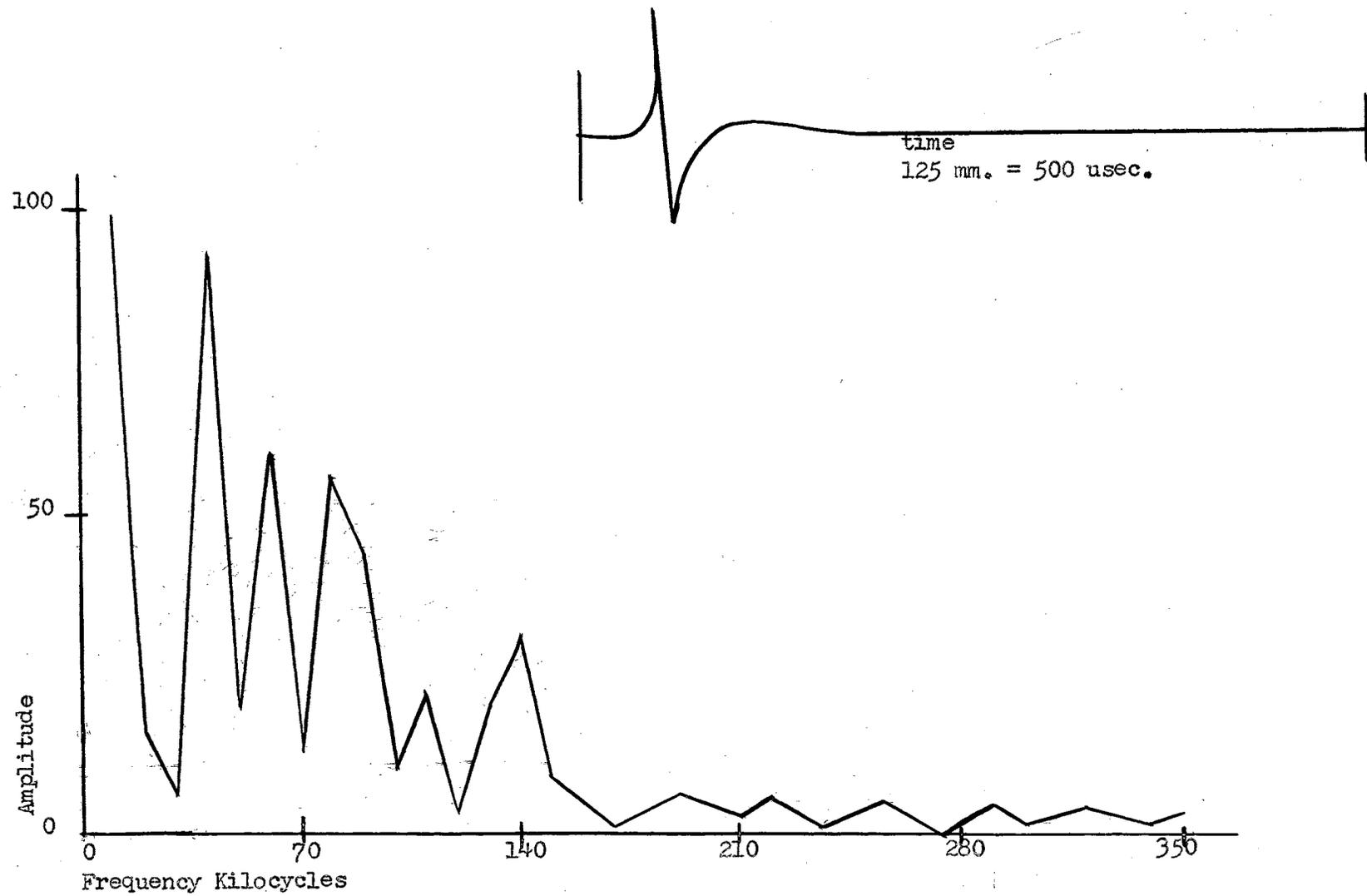
Figure 4-5.   WAVEFORM FREQUENCY SPECTRUM 1

time
125 mm. = 500 usec.
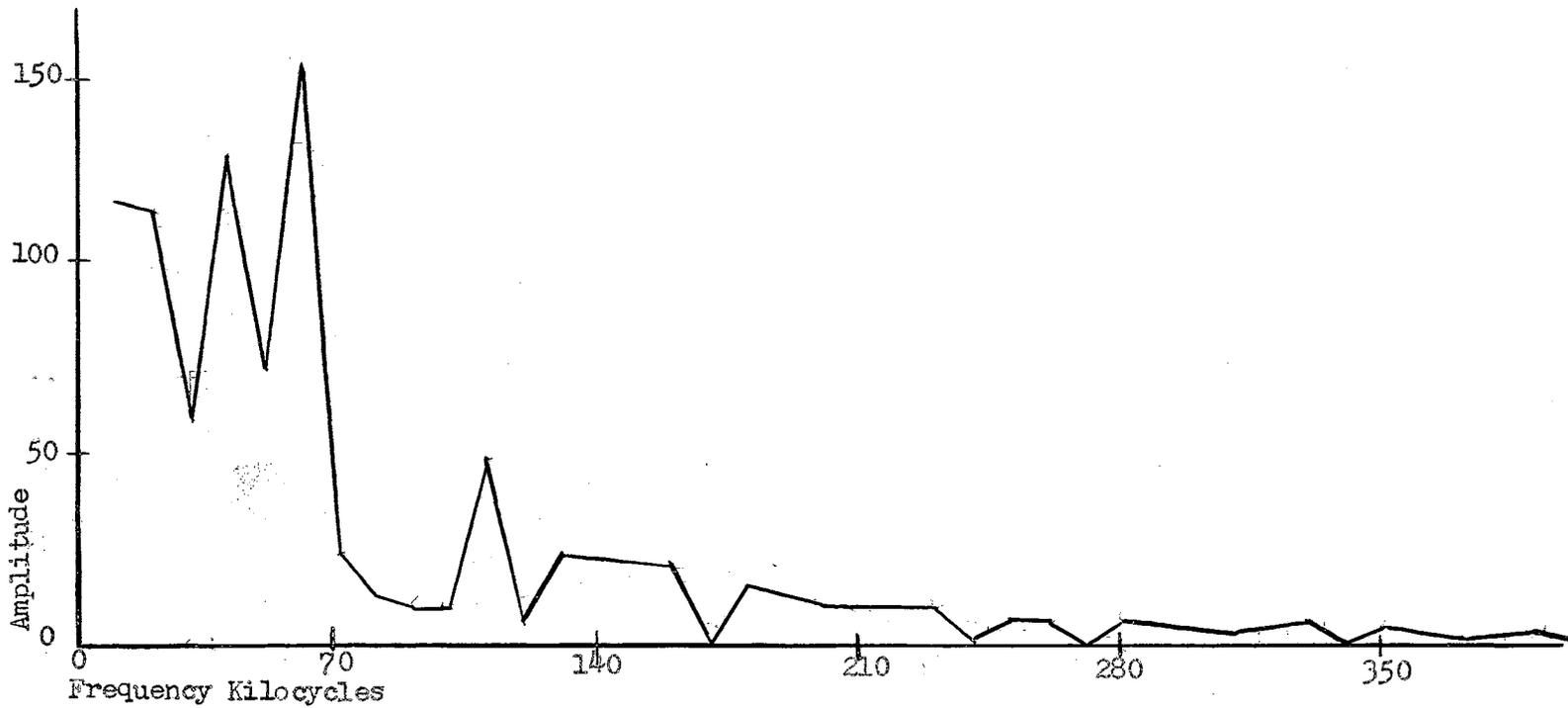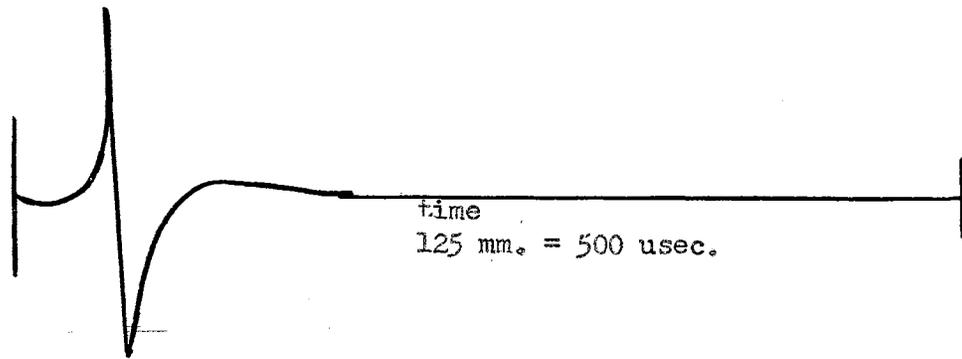
Figure 4-6.   WAVEFORM FREQUENCY SPECTRUM 2

time
125 mm. = 500 usec.
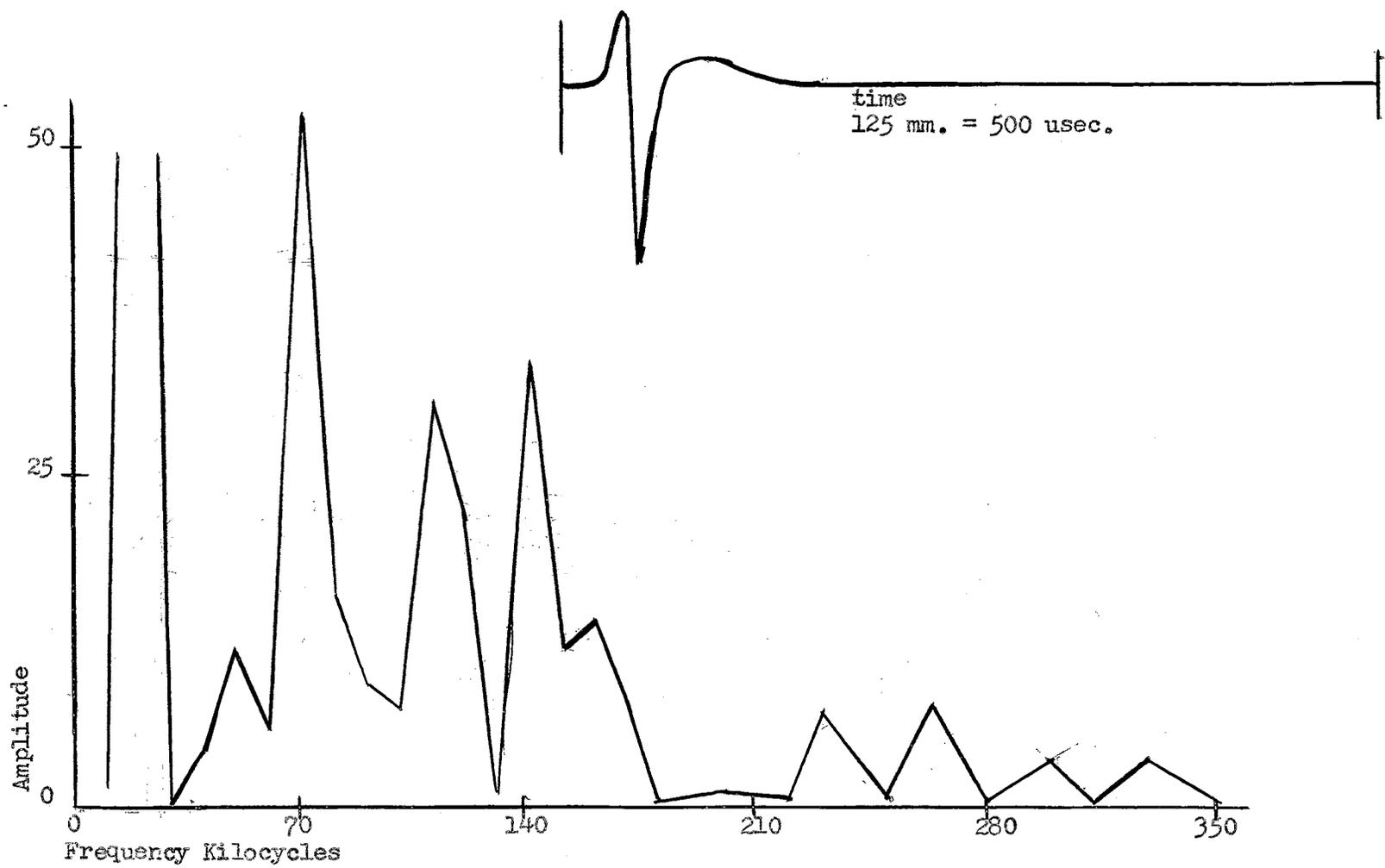
Figure 4-7. WAVEFORM FREQUENCY SPECTRUM 3

time

125 mm. = 500 usec.
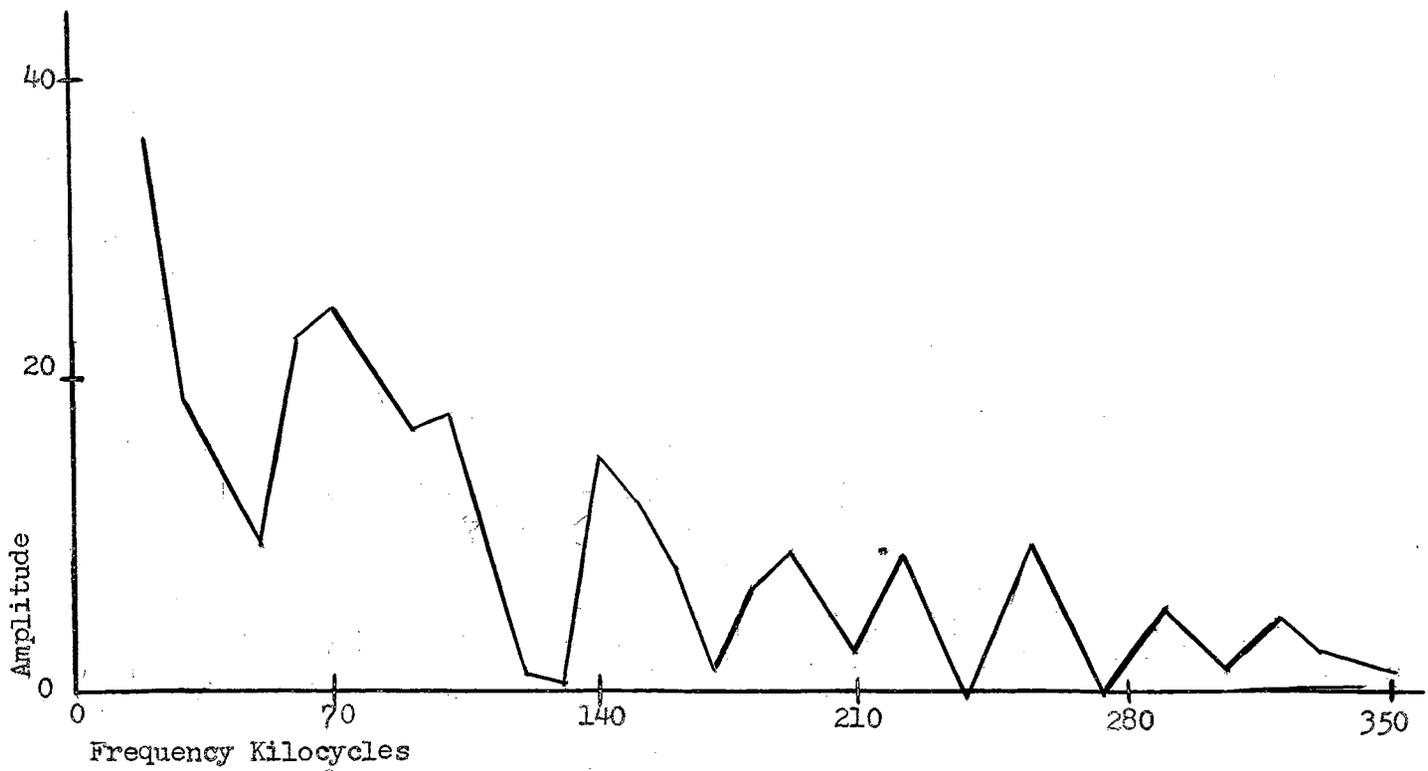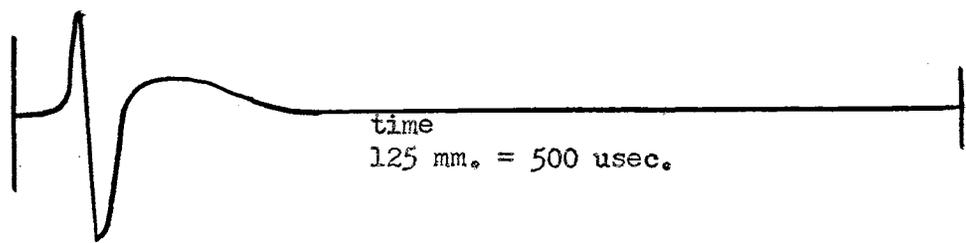
Figure 4-8. WAVEFORM FREQUENCY SPECTRUM 4

time
125 mm. = 500 usec.
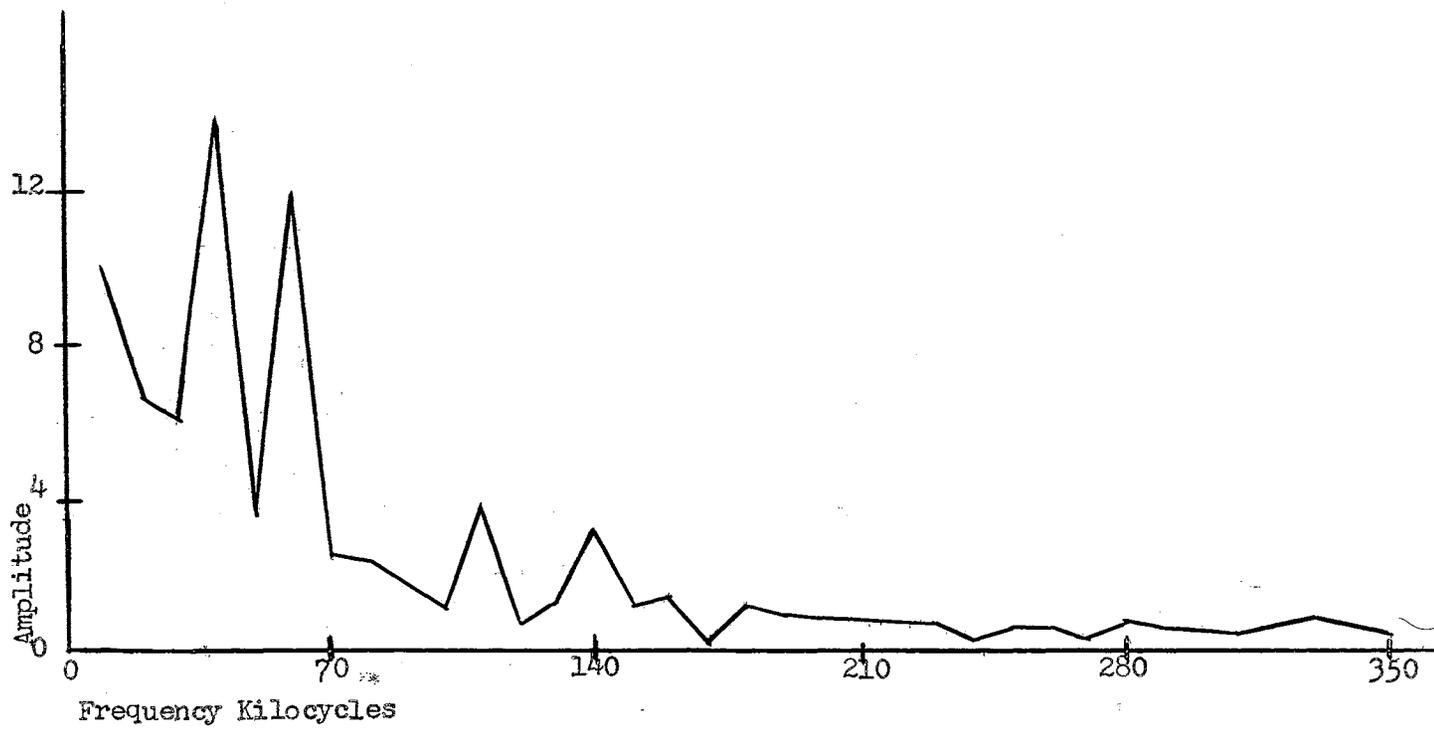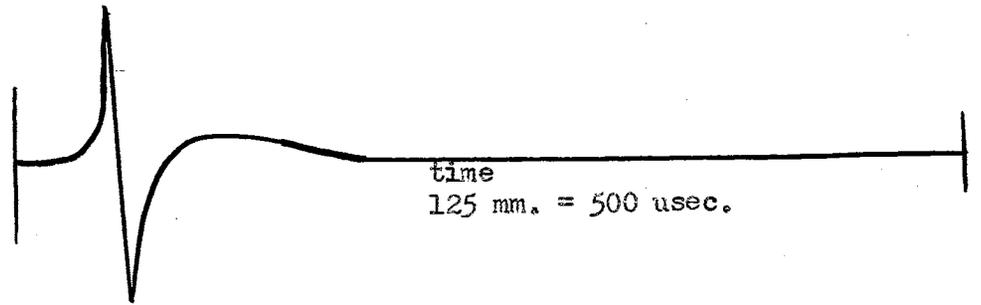
Figure 4-9. WAVEFORM FREQUENCY SPECTRUM 5

Frequency Kilocycles

time
125 mm. = 500 usec.
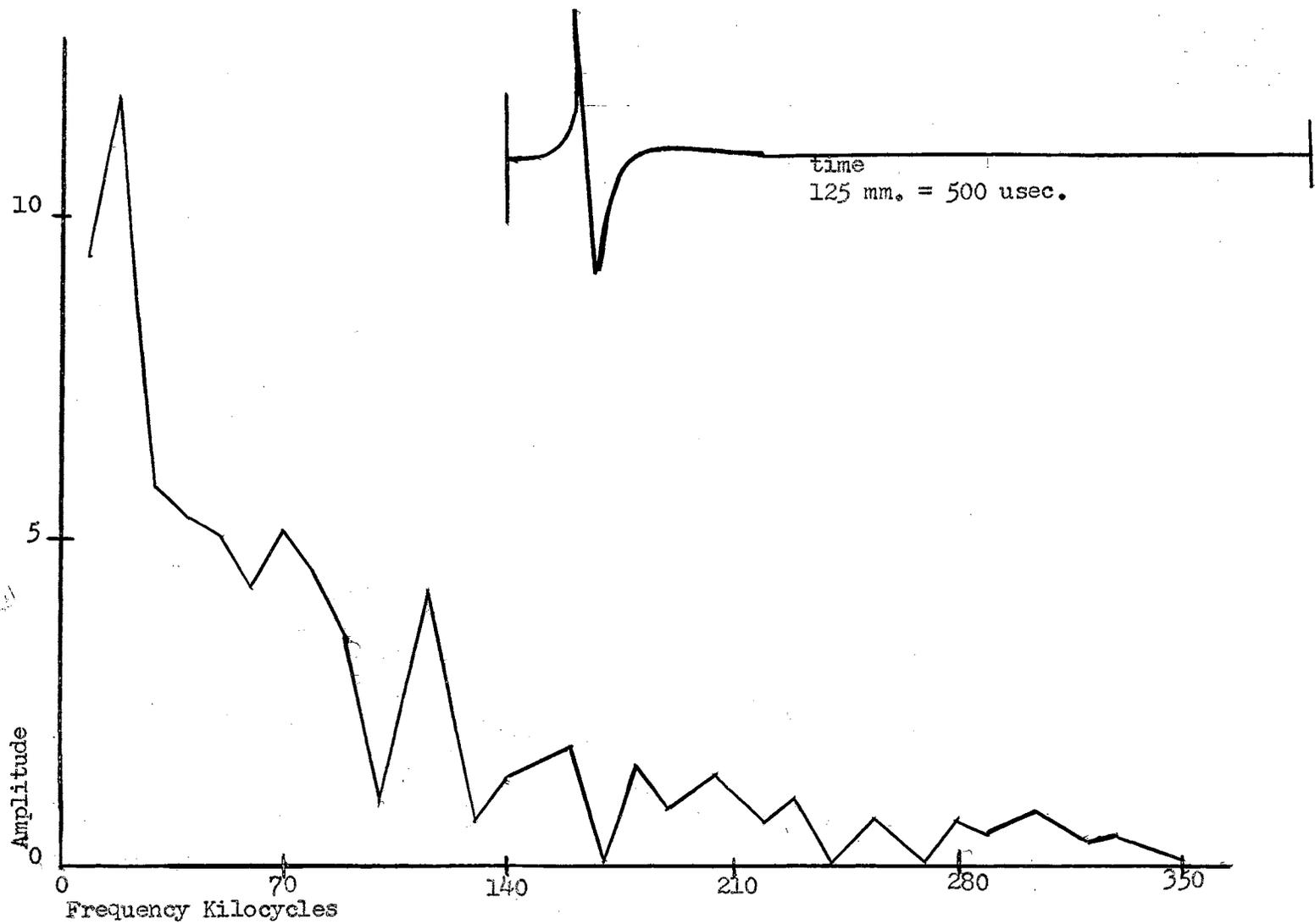
Figure 4-10. WAVEFORM FREQUENCY SPECTRUM 6

time

125 mm. = 500 usec.
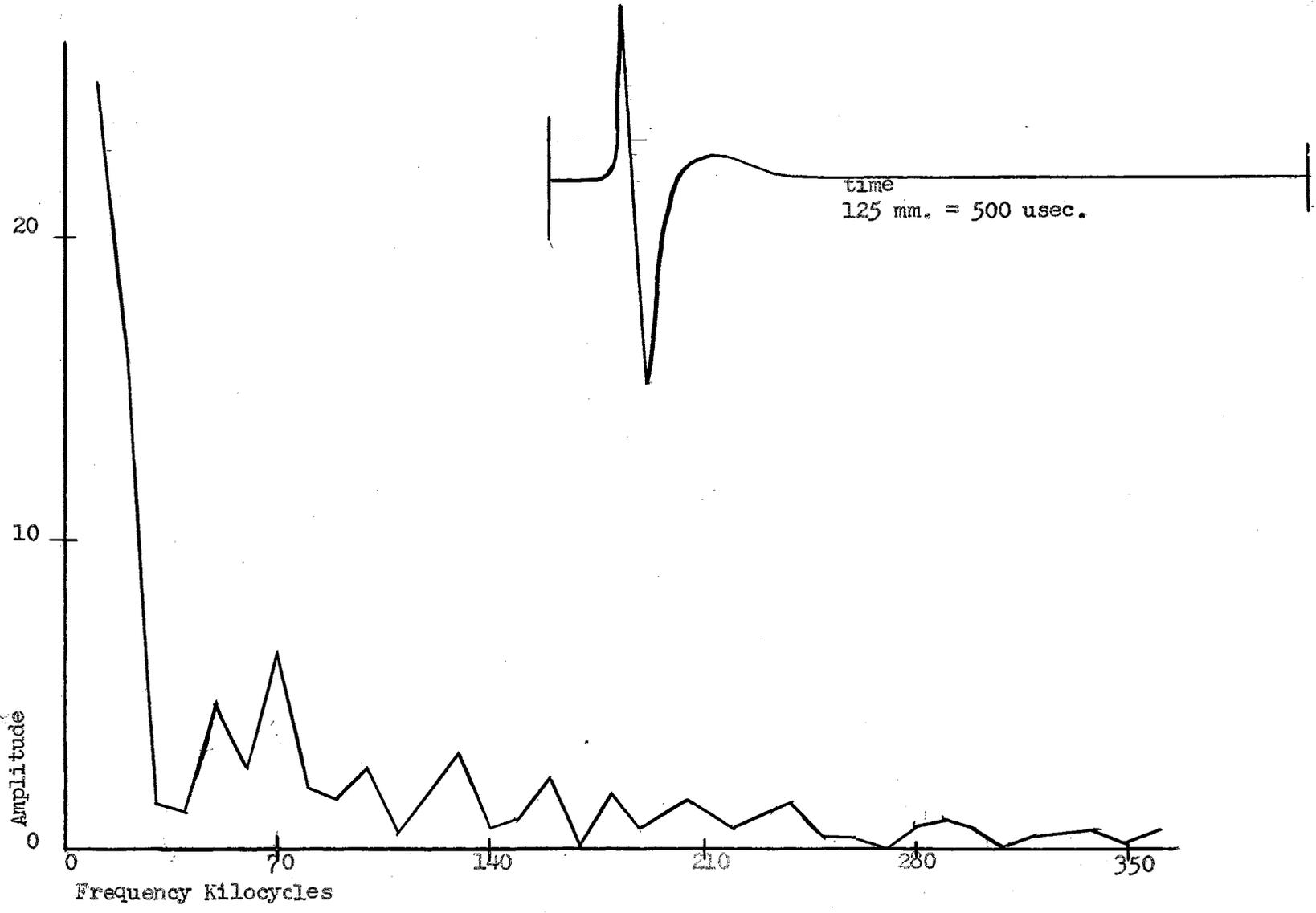
Figure 4-11. WAVEFORM FREQUENCY SPECTRUM 7

time
125 mm. = 500 usec.
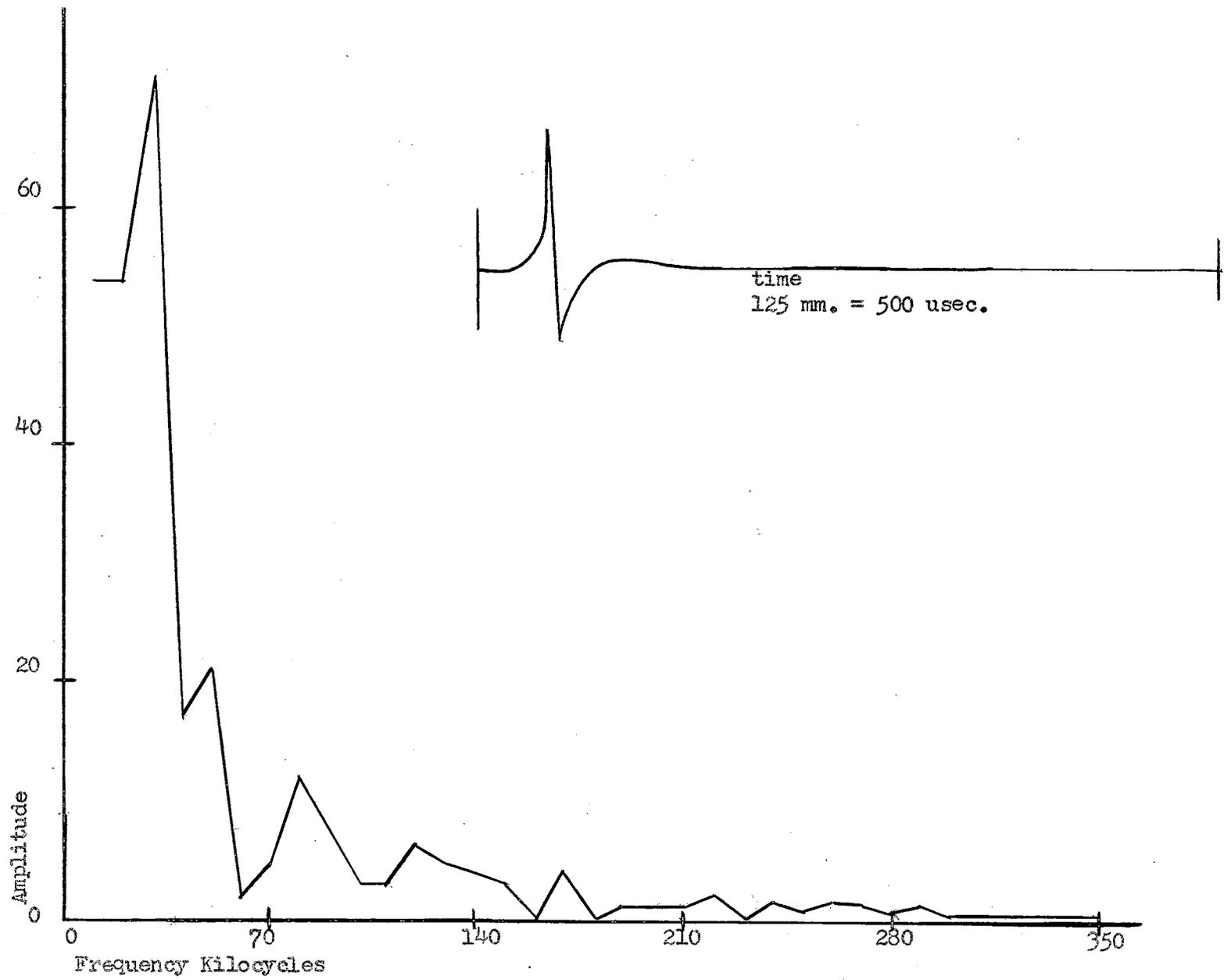
Figure 4-12.   WAVEFORM FREQUENCY SPECTRUM 8

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CHAPTER V

SUMMARY AND CONCLUSIONS

As stated in Chapter I, the most important objective of this thesis is to provide a tool for exploring one of nature's secrets, the electromagnetic waveform of the severe thunderstorm lightning discharge. Consequently in Chapter II, a development of the Fourier Integral was presented. This affords a mathematical method for determining the frequency spectrum of a non-repeating pulse or waveform. Use of the mathematical tool, however, involves a series of long-repeated steps in order to arrive at the desired result. Therefore, in Chapter III a program for the IBM 650 computer was developed. This program affords two distinct advantages: first, high computation speed and second, freedom from computational errors. A complete compute diagram, program description, and program listing are given to facilitate ease of use by possible future researchers. In Chapter IV attention is turned to the technical aspects of collecting, sorting, and readying of the waveform data for analysis. Also in Chapter IV a waveform theory is presented and the waveforms and their spectra are given.

Suggestions for Future Research

For future research it is the author's thought that each type of lightning discharge quite possibly has an associated waveform. If this is so, then there is an associated frequency spectrum for each type. A

method of correlation between a given recorded waveform and the lightning
discharge which caused it would allow for typing the sferic according to
frequency content. Thus cloud-to-ground, cloud-to-cloud, and inter-cloud
lightning, and any sub-classifications or types, could be definitely
identified by their respective frequency spectra. One correlation
method already exists in the equipment constructed by Boudreaux in 1959
in combination with the waveform recording equipment. This equipment
is at present operational and requires only a number of severe storms
to furnish all the data necessary for correlation studies.

Conclusions

It was found that ease of waveform spectra computation far exceeded
the author's expectations. Further, the physical observations of the
waveforms and their spectra agreed very well with theory. The work
contained herein is far from complete. However, with the foundation
now laid, intensive investigations of waveform spectra are possible
and relatively easy to perform.

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