COMPUTER ANALYSIS OF SFERIC WAVEFORMS

By

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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 whose sense of humor afforded many enjoyable moments and whose advice was often sought and freely given. To Mrs. Cassie Spencer of the Computing Center staff many thanks are given for her invaluable aid. 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.

TABLE OF CONTENTS

LIST OF FIGURES

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 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

$$f(t) = a_o/2 + \sum_{1}^{\infty}(a_n \cos nwt + b_n \sin nwt) \tag{2-2}$$

where

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

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

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

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, Waveform Analysis, 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

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

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

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

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

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

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 $\lim_{T \to \pm\infty} 1/T = \lim_{T \to \pm\infty} w_o/2\pi = 0$

and also in the limit $\Delta nw_o = dw$ and $nw_o = w$. 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

$$f(t) = 1/2 \int_{-\infty}^{+\infty} a(w) \cos wt + b(w) \sin wt + j \left[a(w) \sin wt - b(w) \cos wt \right] dw. \qquad (2\text{-}24)$$

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 $+\infty$ only. Equation (2-24) is easily reduced to the required form. Let

$$c(w) = \left[a(w)^2 + b(w)^2 \right]^{1/2} \qquad (2\text{-}25)$$

and

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

then

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

where c (w) is the amplitude function and θ(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

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

where

$$M = \frac{f'' - f'}{t'' - t'} \tag{2-30}$$

Therefore the equation for a (w) is

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

which readily reduces to

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

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

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

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.) $M/w^2(\cos wt'' - \cos wt') = \text{delta } a(w)$ -- store (63-66).

(11.) $\sin wt'' = \sin B$ --- store (67-69).

(12.) $M/w^2(\sin wt'' - \sin wt') = \text{delta } b(w)$ -- 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.) $[b\ (w)]^2$ ----------- store (82-84).

(16.) $[a\ (w)]^2$ (85-86).

(17.) $[b\ (w)]^2 + [a\ (w)]^2$ (87).

(18.) $c\ (w) = \{[b\ (w)]^2 + [a\ (w)]^2\}^{1/2}$ --- 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 numbered 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 compute 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
            EQU  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
```

```
        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
```

```
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     ÇOSASTR          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	PCHB	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 description of all the equipment shown may be found in the respective equipment

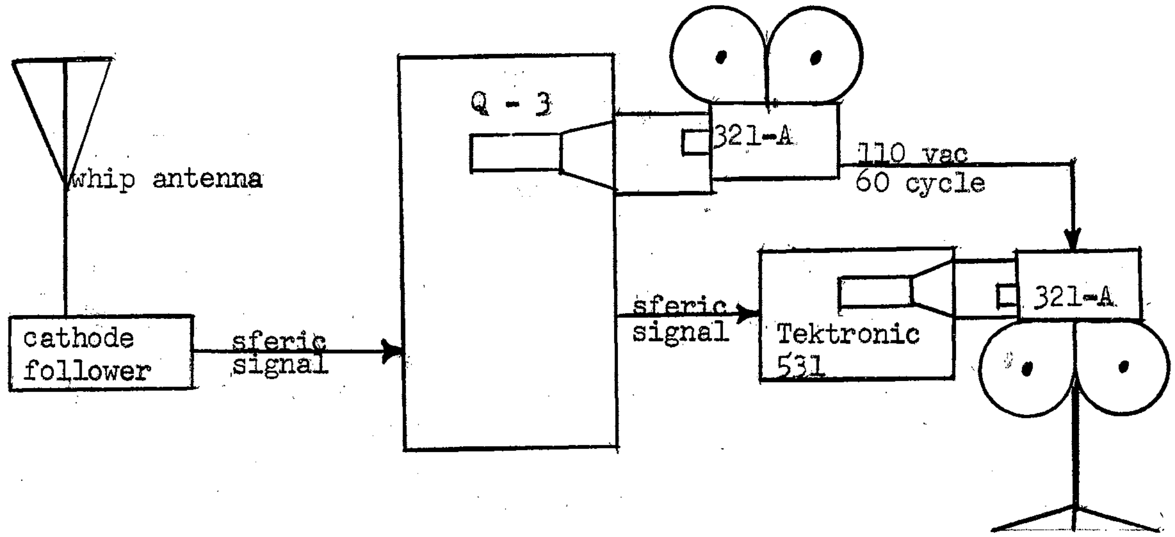

Figure 4.1. Block Diagram

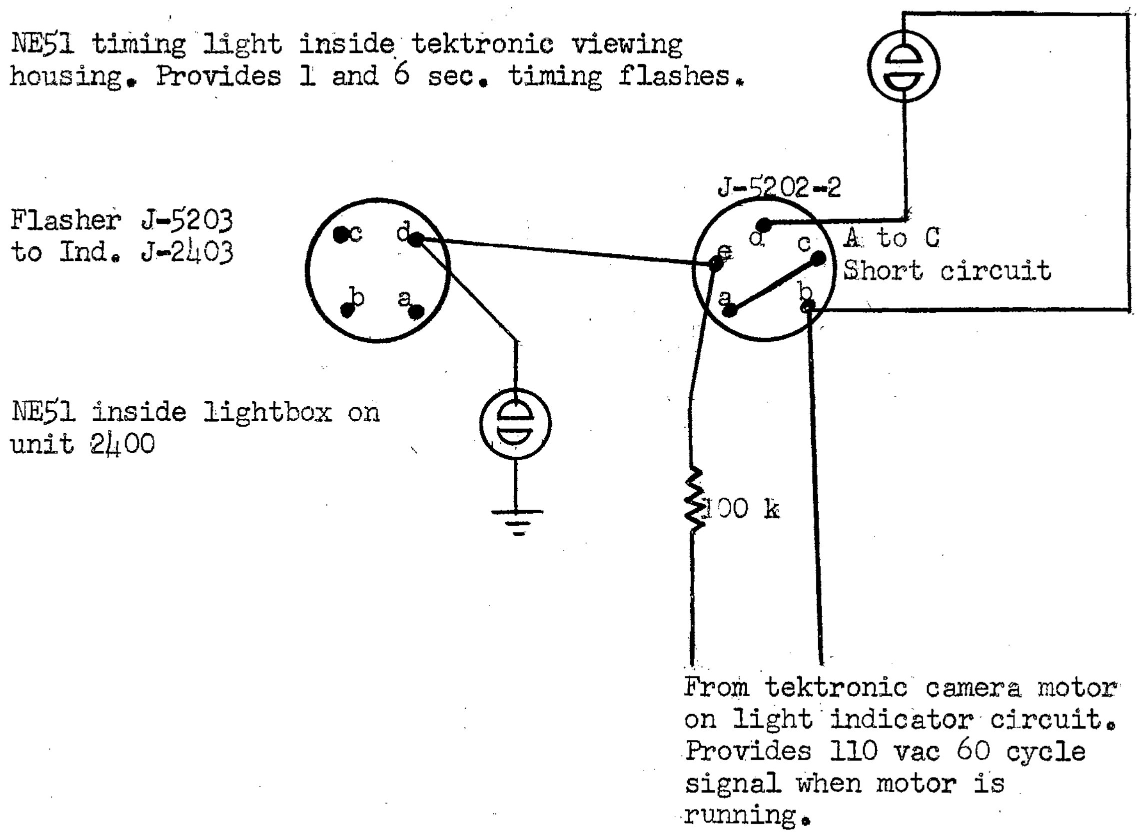

Figure 4.2. Wiring Diagram

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 4.4a]. 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 4.4b]. An exponential decay of the

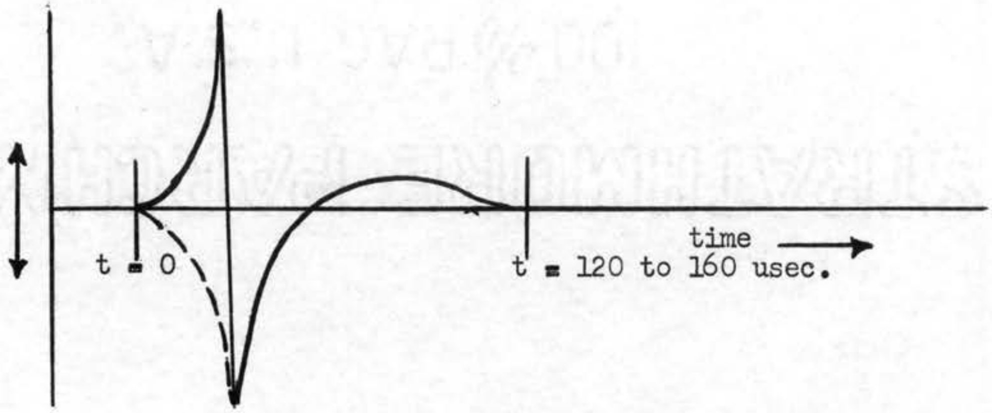

Figure 4.3. Sferic Waveform Example

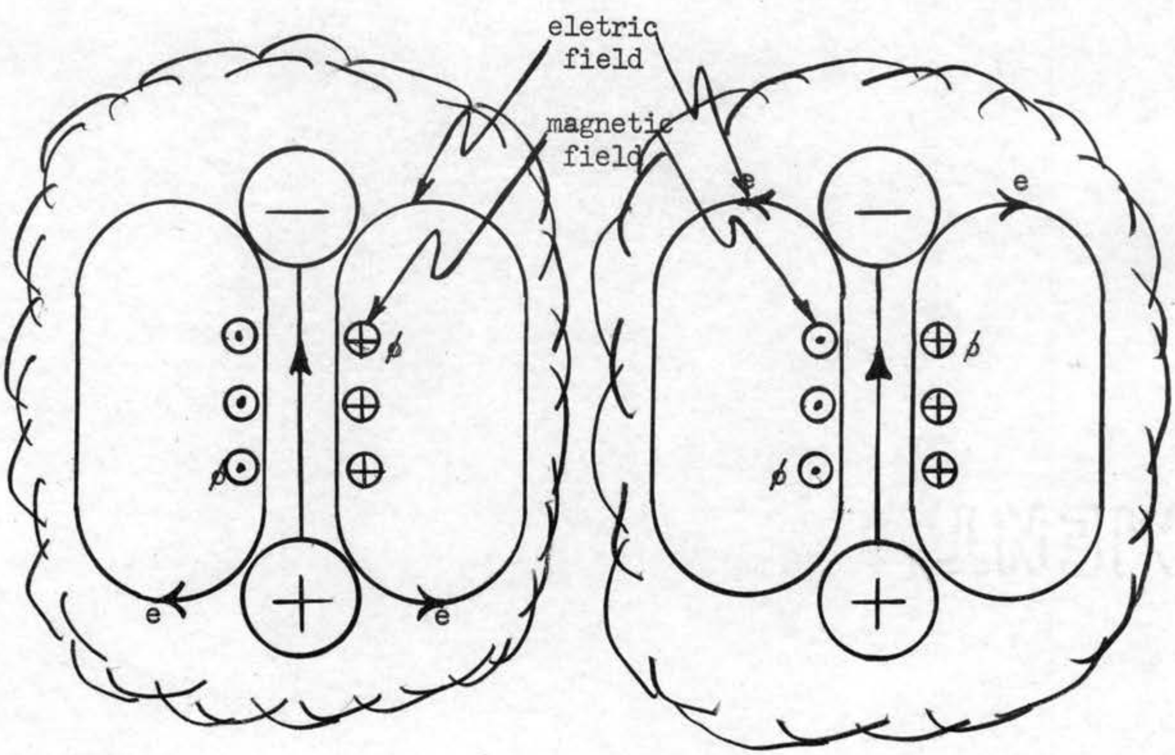

Figure 4.4a. Increasing Current   Figure 4.4b. Decreasing Current

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.

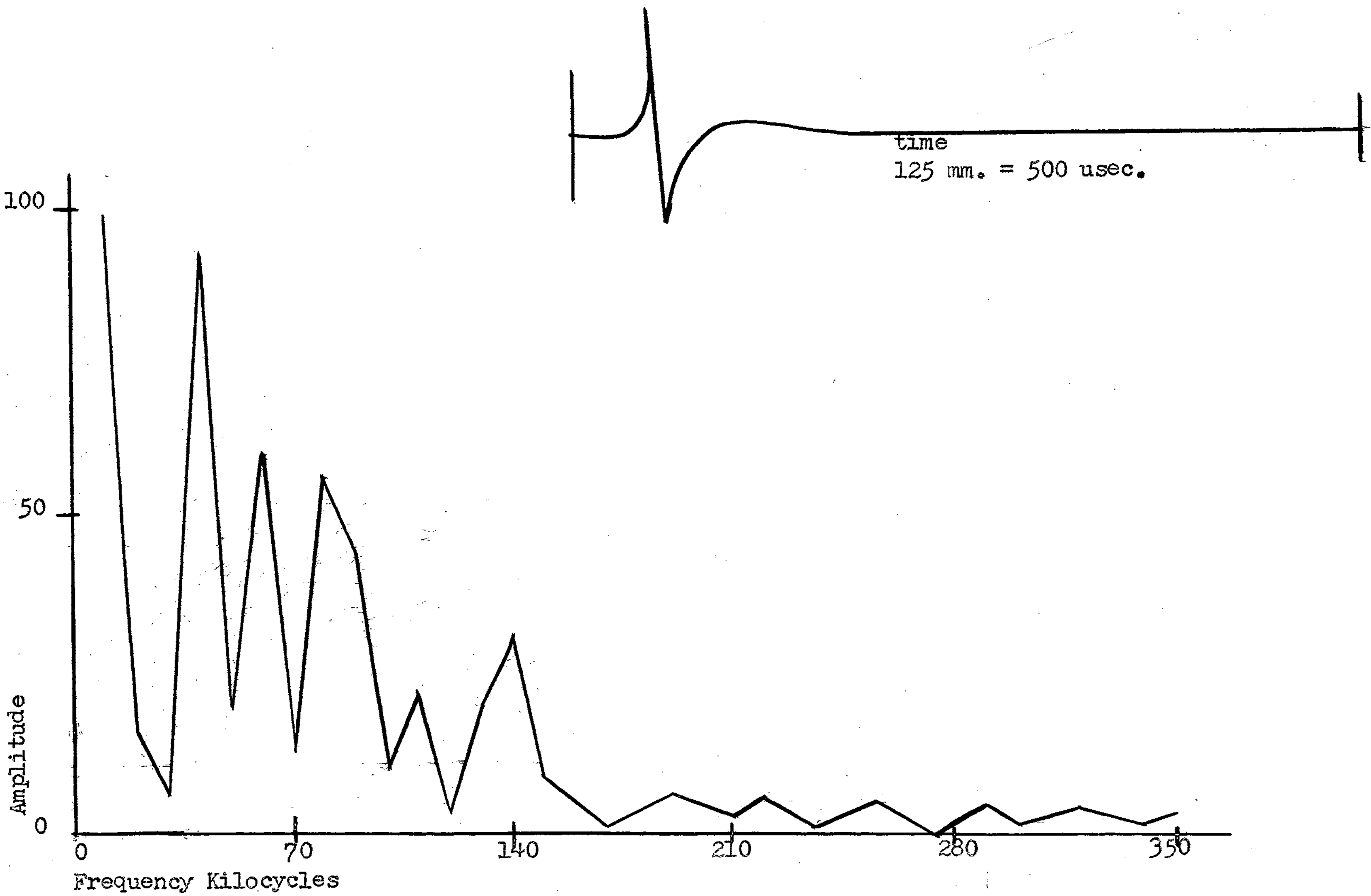

Figure 4-5. WAVEFORM FREQUENCY SPECTRUM 1

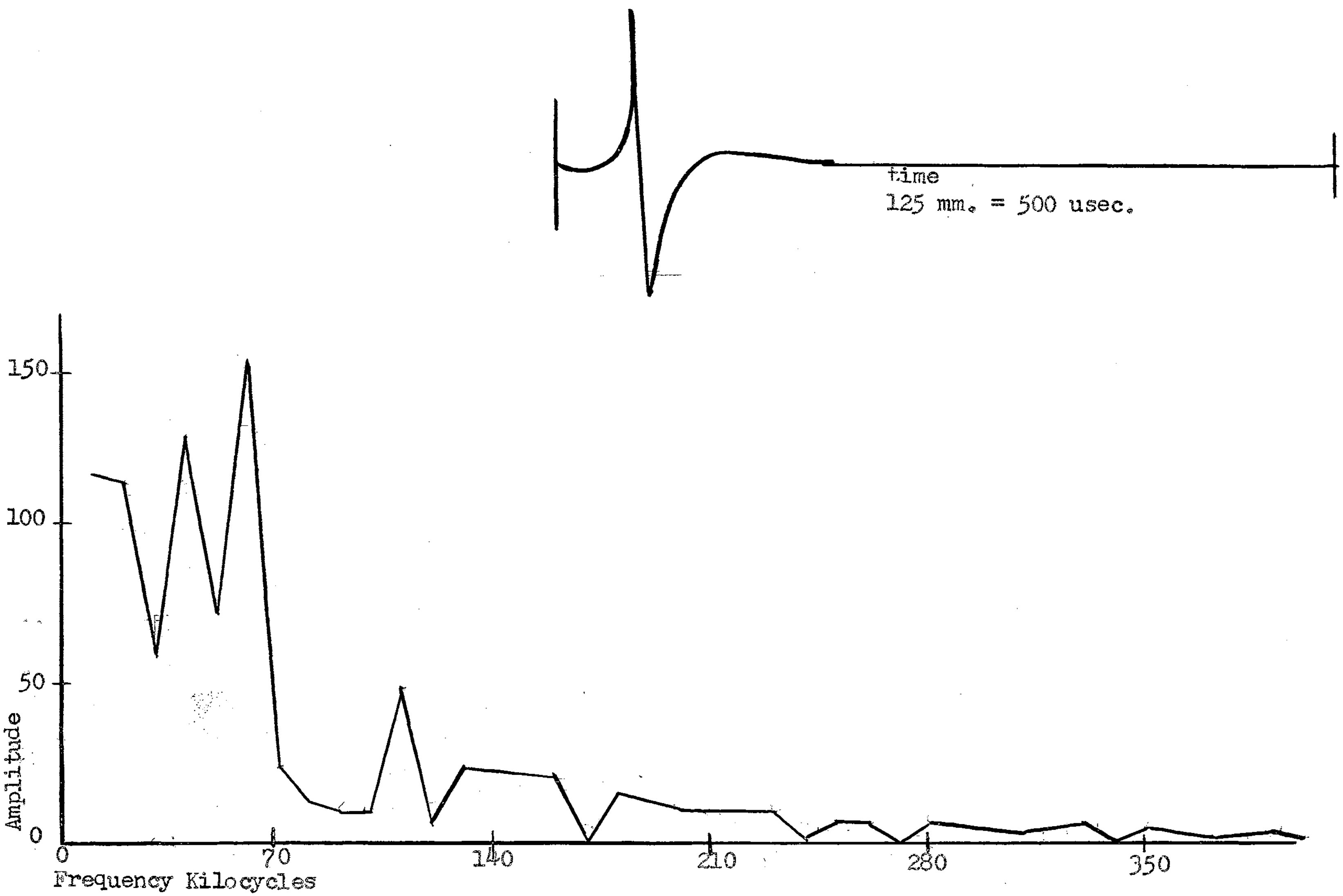

Figure 4.6. WAVEFORM FREQUENCY SPECTRUM 2

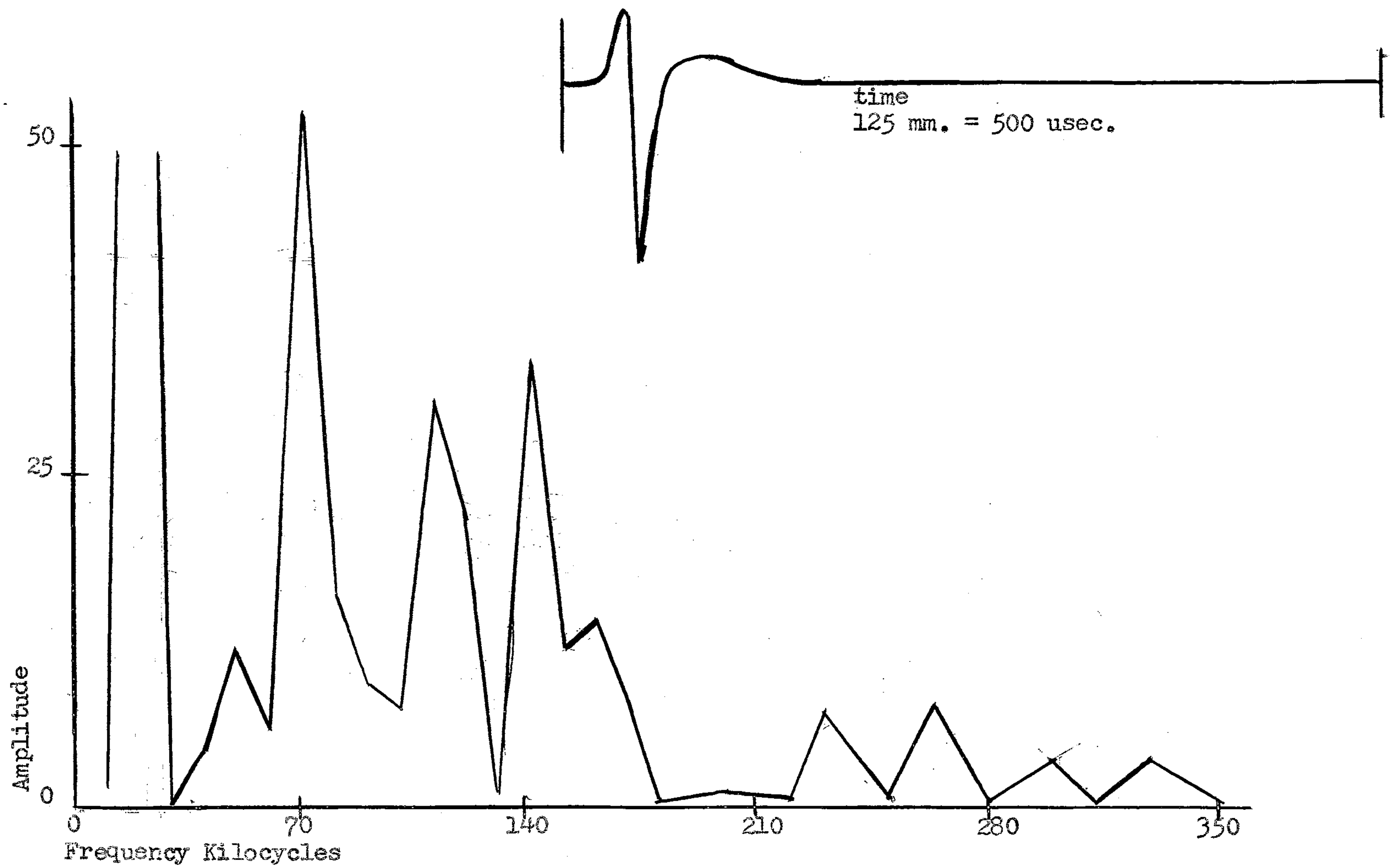

Figure 4-7. WAVEFORM FREQUENCY SPECTRUM 3

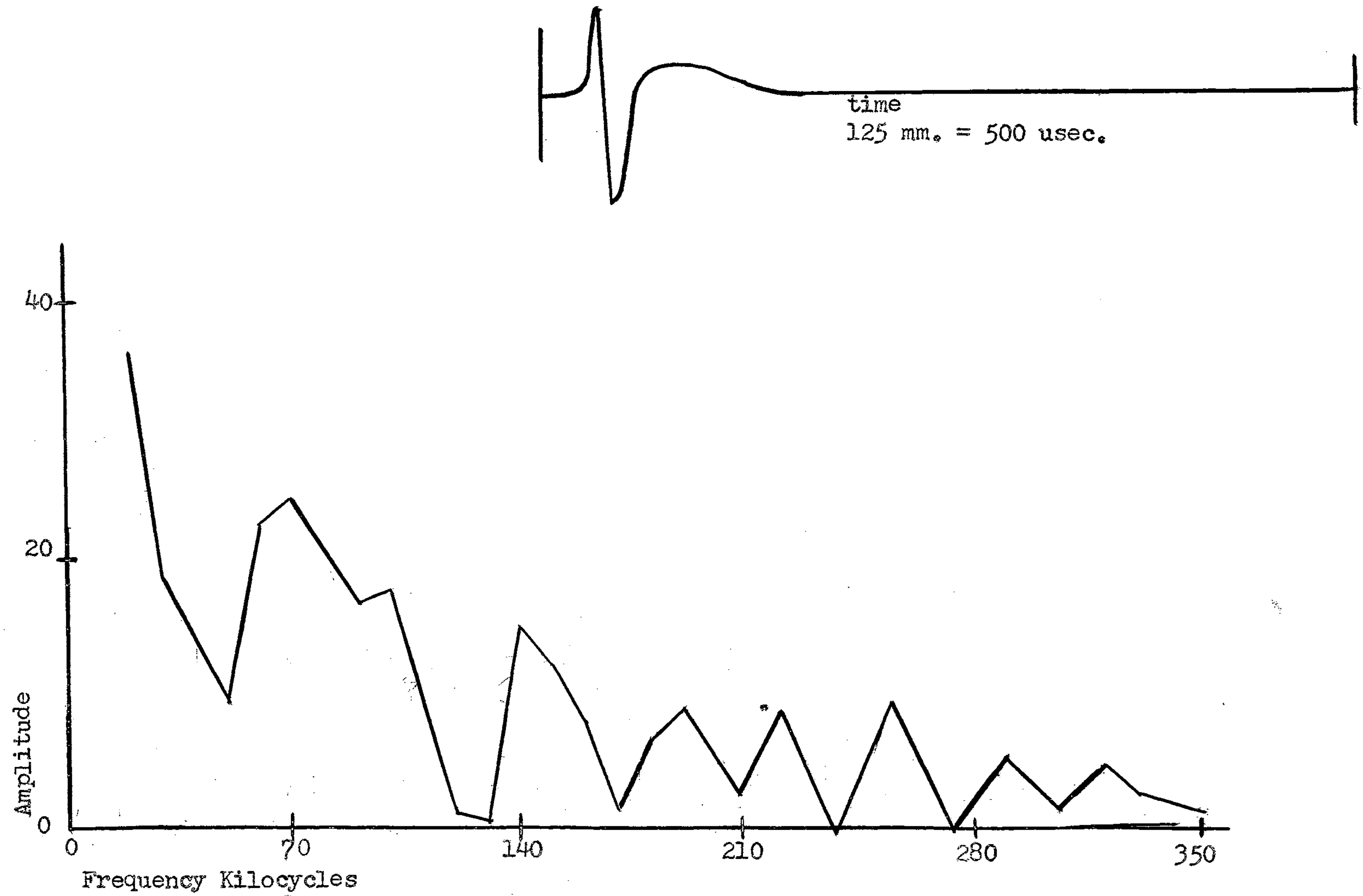

Figure 4.8. WAVEFORM FREQUENCY SPECTRUM 4

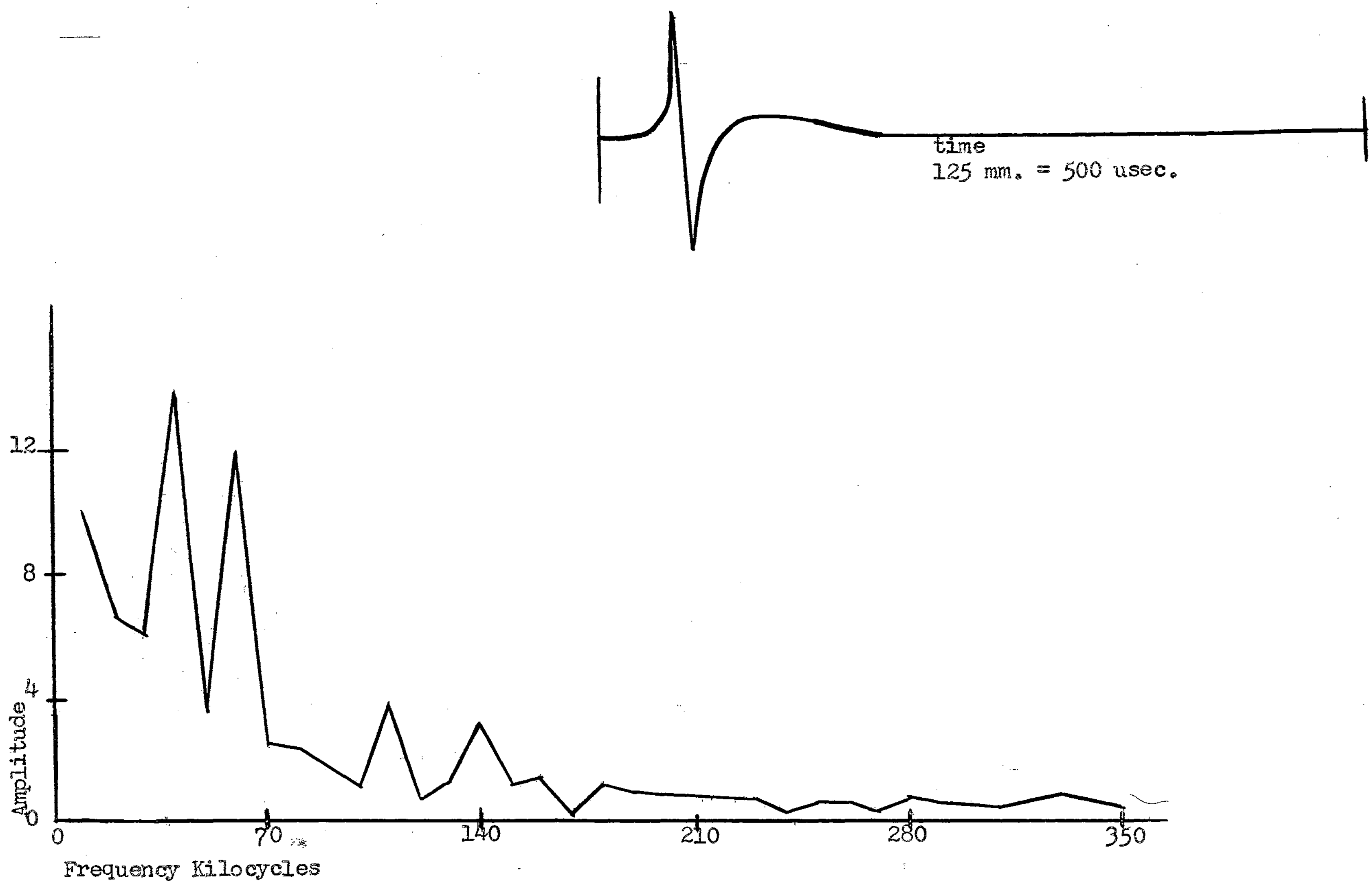

Figure 4-9. WAVEFORM FREQUENCY SPECTRUM 5

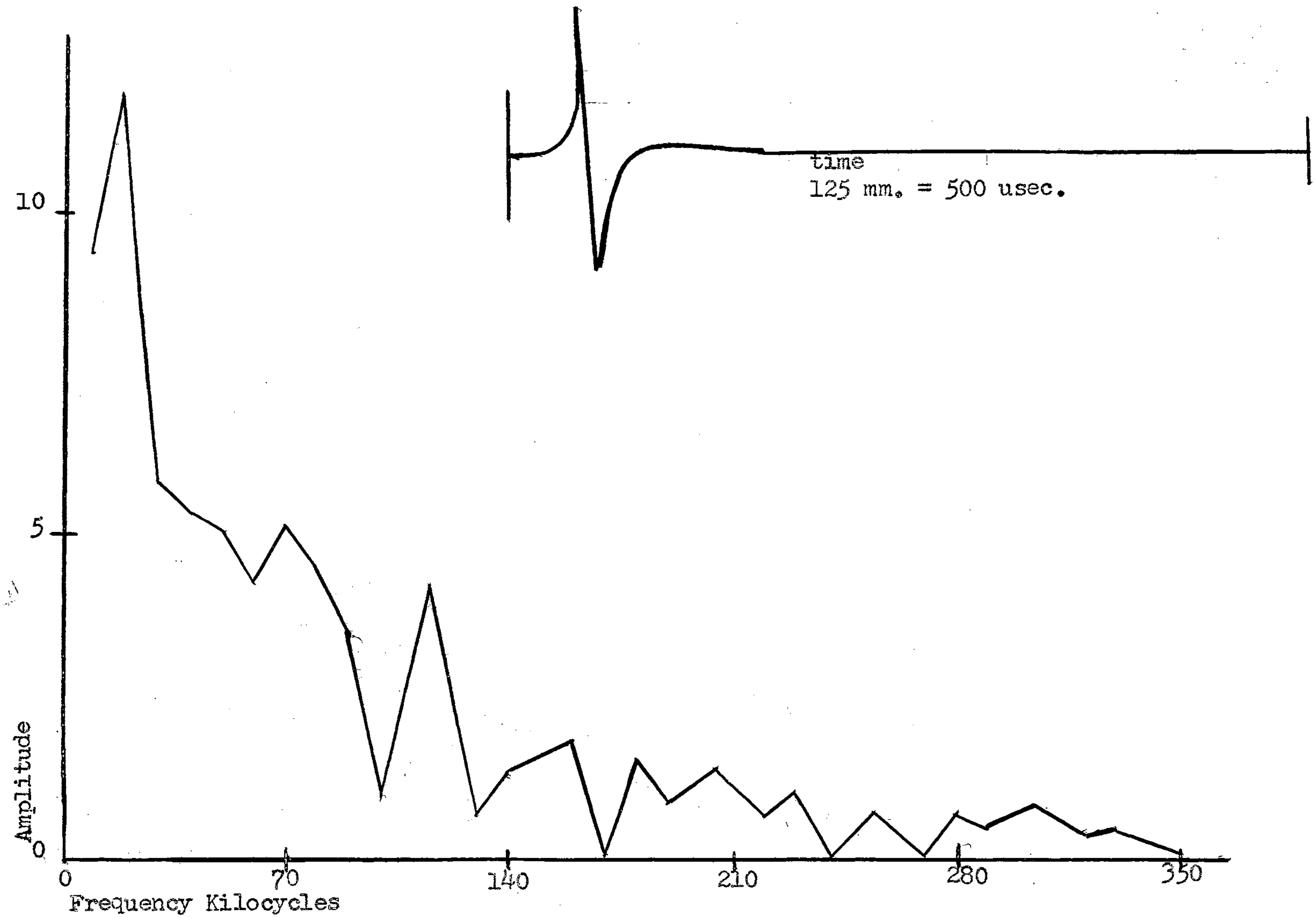

Figure 4-10. WAVEFORM FREQUENCY SPECTRUM 6

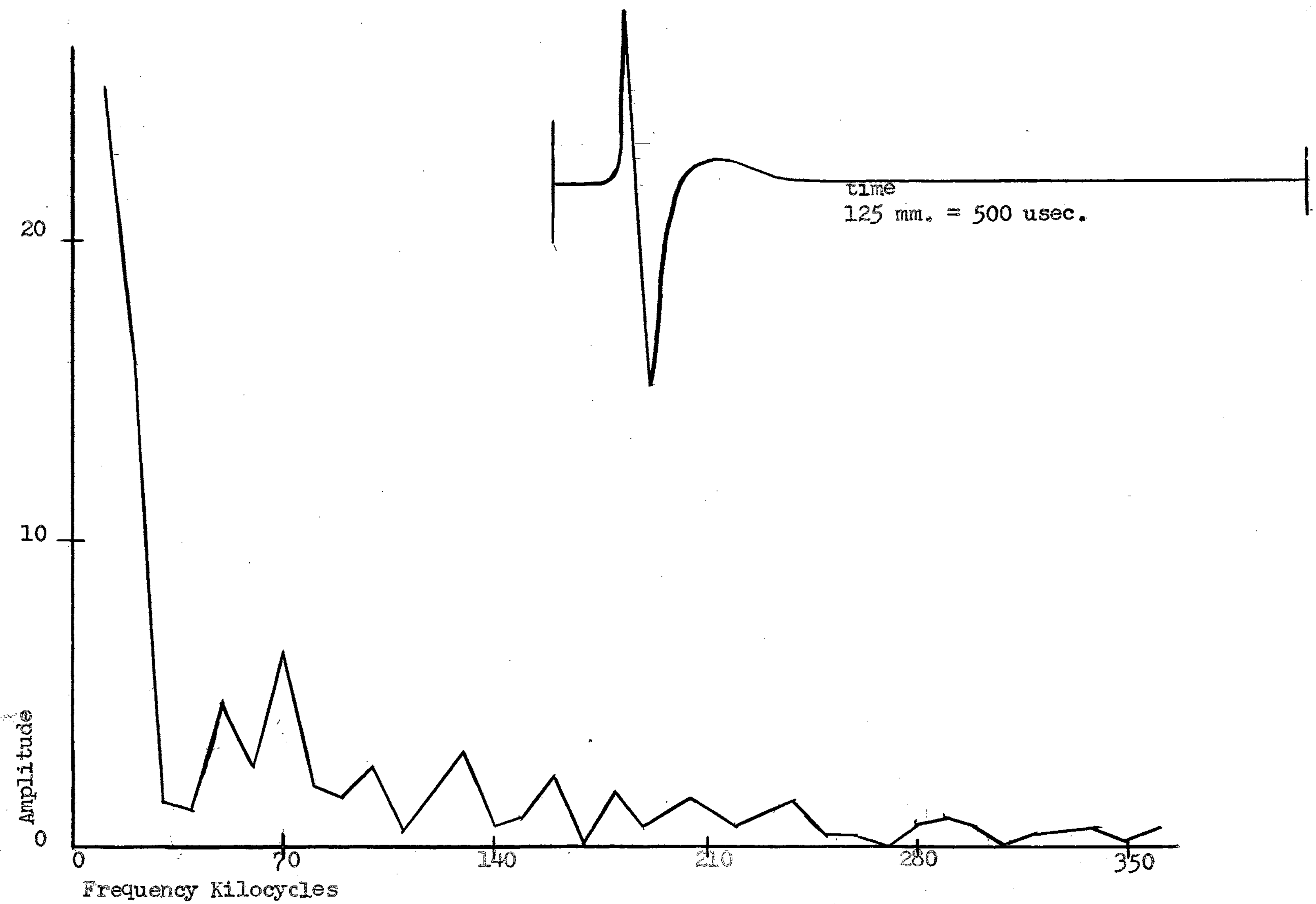

Figure 4.11. WAVEFORM FREQUENCY SPECTRUM 7

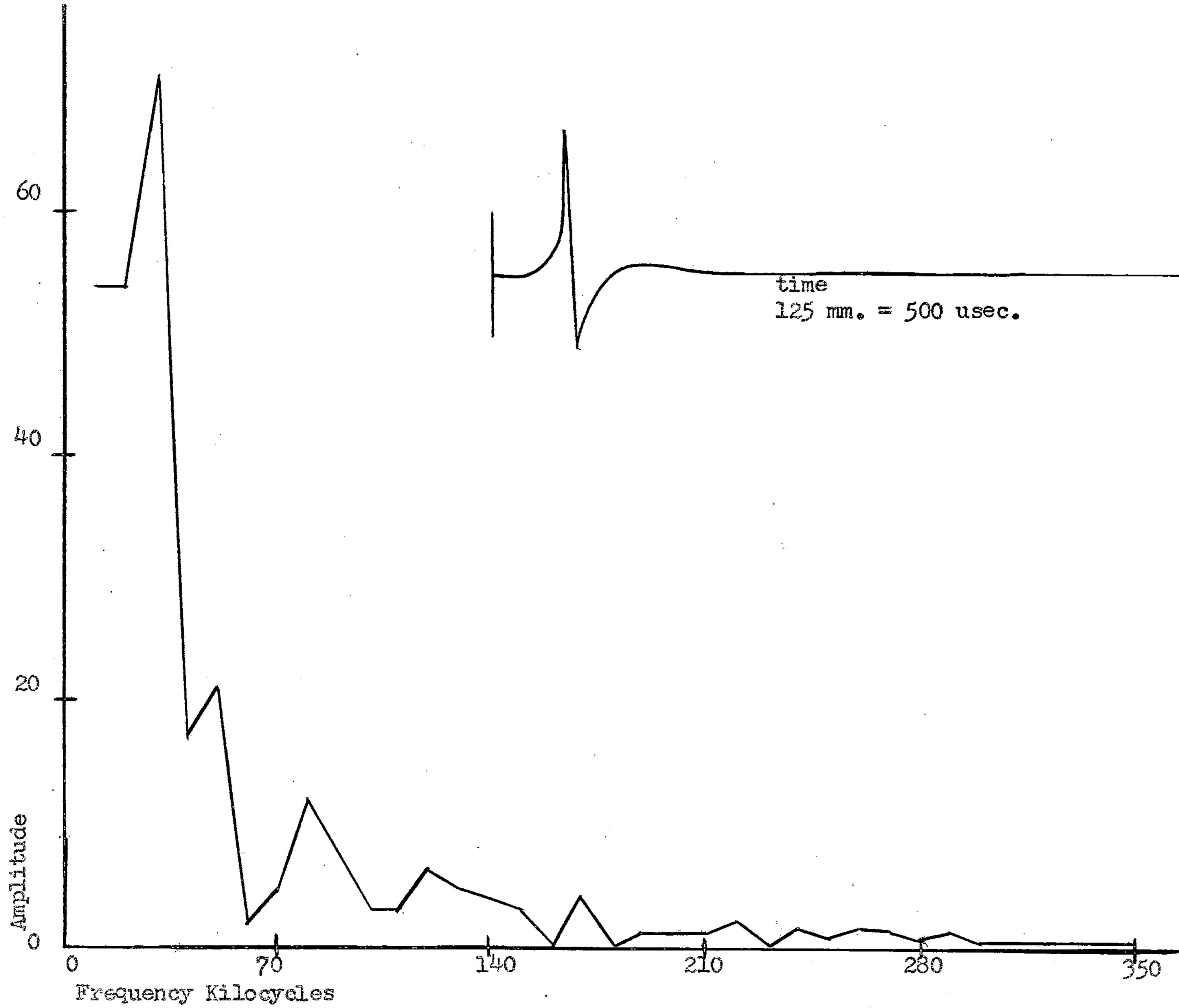

Figure 4-12. WAVEFORM FREQUENCY SPECTRUM 8

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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