More on the Tesla/Alexanderson System of Wireless Transmission and It's Application at Bolinas, CA
Part 2

…where time can flow backward and energy transmission can be instantaneous.

San Francisco Tesla Society

CHAPTER IX.

WAVES FROM MOVING SOURCES.

Adagio. Andante. Allegro moderato.

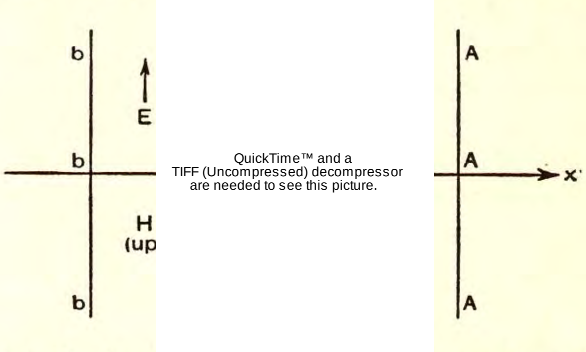
§ 450. The following story is true. There was a little boy, and his father said, "Do try to be like other people. Don't frown." And he tried and tried, but could not. So his father beat him with a strap; and then he was eaten up by lions.

Reader, if young, take warning by his sad life and death. For though it may be an honour to be different from other people, if Carlyle's dictum about the 30 millions be still true, yet other people do not like it. So, if you are different, you had better hide it, and pretend to be solemn and wooden-headed. Until you make your fortune. For most wooden-headed people worship money; and, really, I do not see what else they can do. In particular, if you are going to write a book, remember the wooden-headed. So be rigorous; that will cover a multitude of sins. And do not frown.

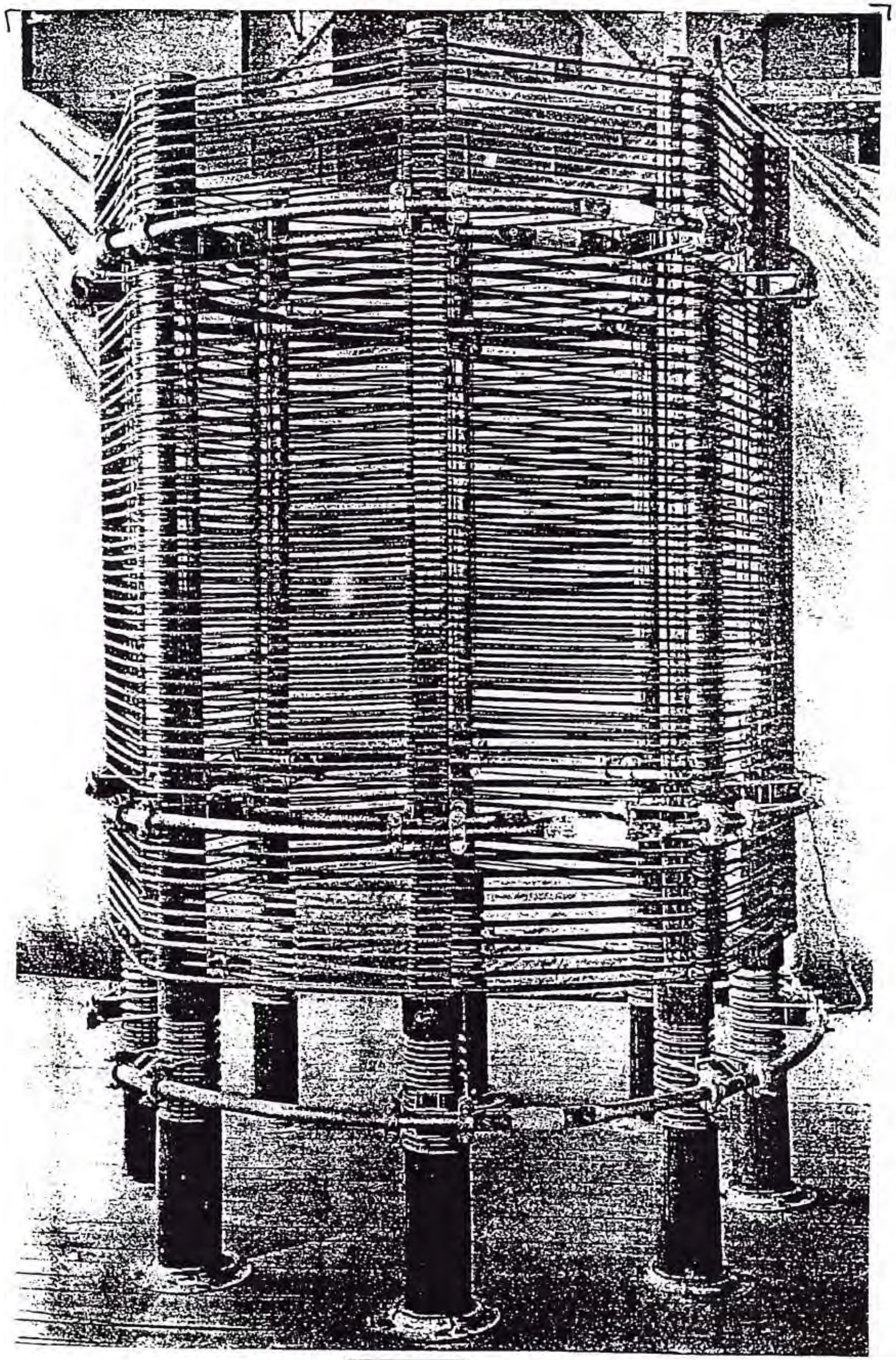
There is a time for all things: for shouting, for gentle speaking, for silence; for the washing of pots and the writing of books. Let now the pots go black, and set to work. It is hard to make a beginning, but it must be done.

Simple Proof of Fundamental Property of a Plane Wave.

§ 451. At present, in dealing with some elementary properties, the object is to smooth the road to the later matter. First of all, how prove the fundamental property of a plane wave, that it travels at constant speed undistorted, if there be no conductivity, or, more generally, no molecular interference causing dispersion and other disturbances? We have merely



to show that the two circuital laws are satisfied, and that can be done almost by inspection. Thus, let the region between two parallel planes *aaa* and *bbb* be an electric field and a



8-28 Tuning Inductance for Multiple Tuned Antenna (Series Coil)

Tuning Coils

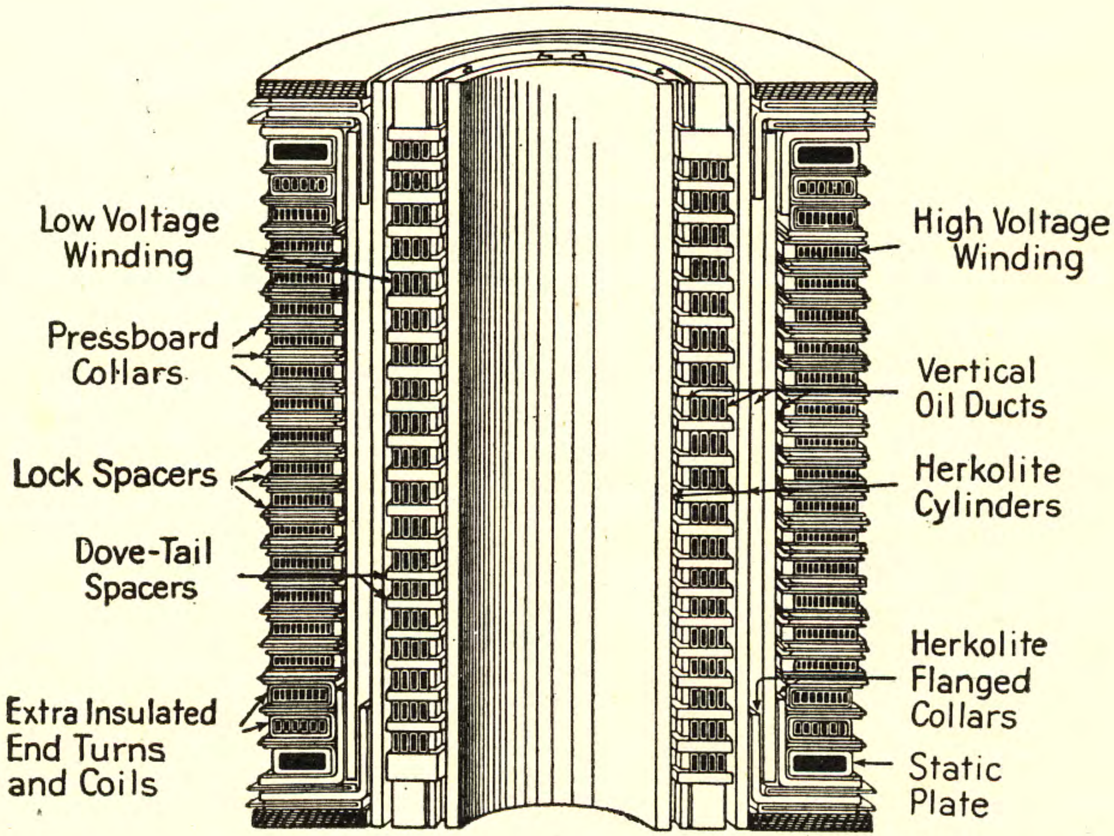


FIG. 97.—Cross-Section of Comparatively High-Voltage Power Transformer

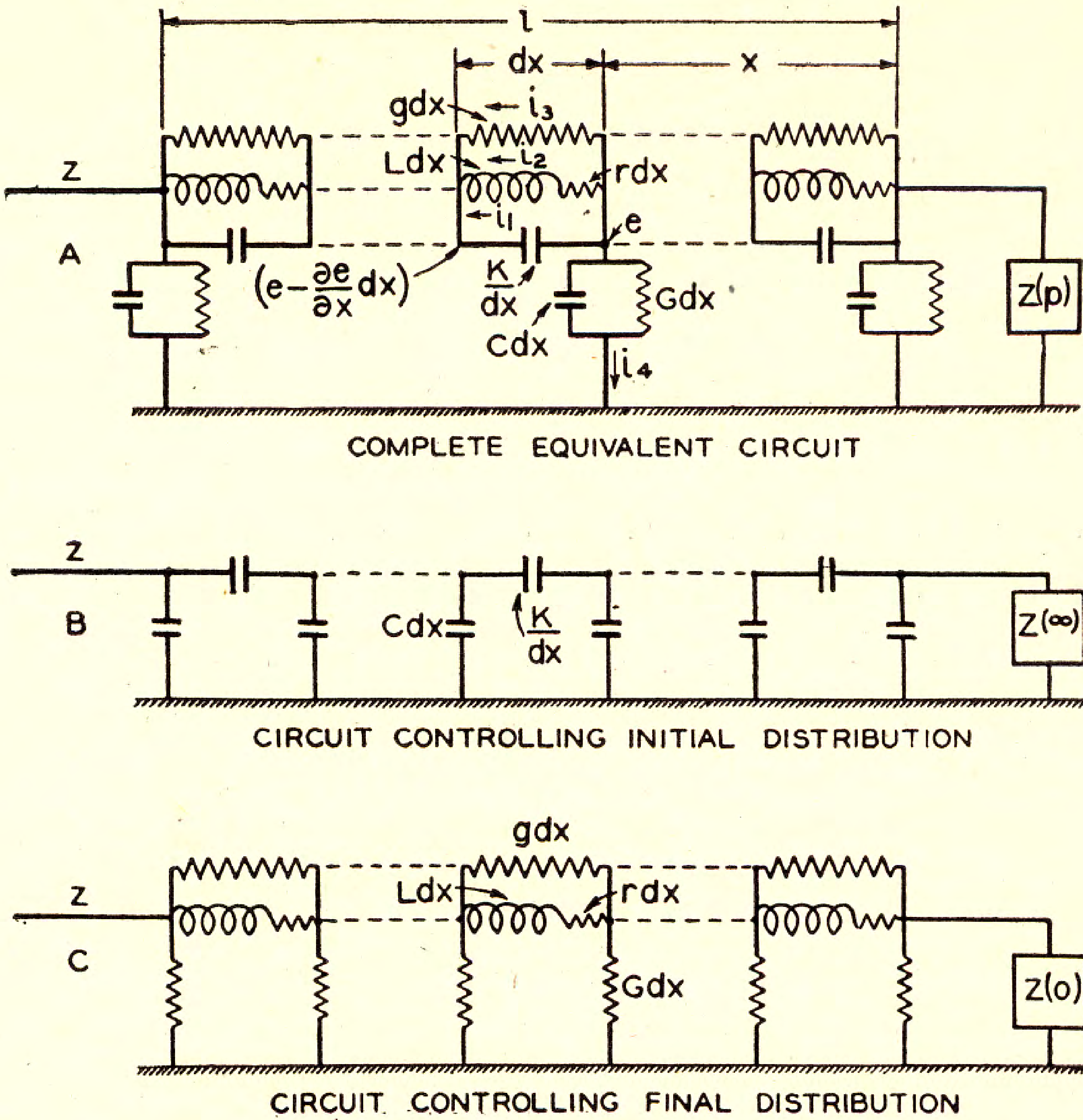


FIG. 103.—Ideal Complete Circuit of a Winding

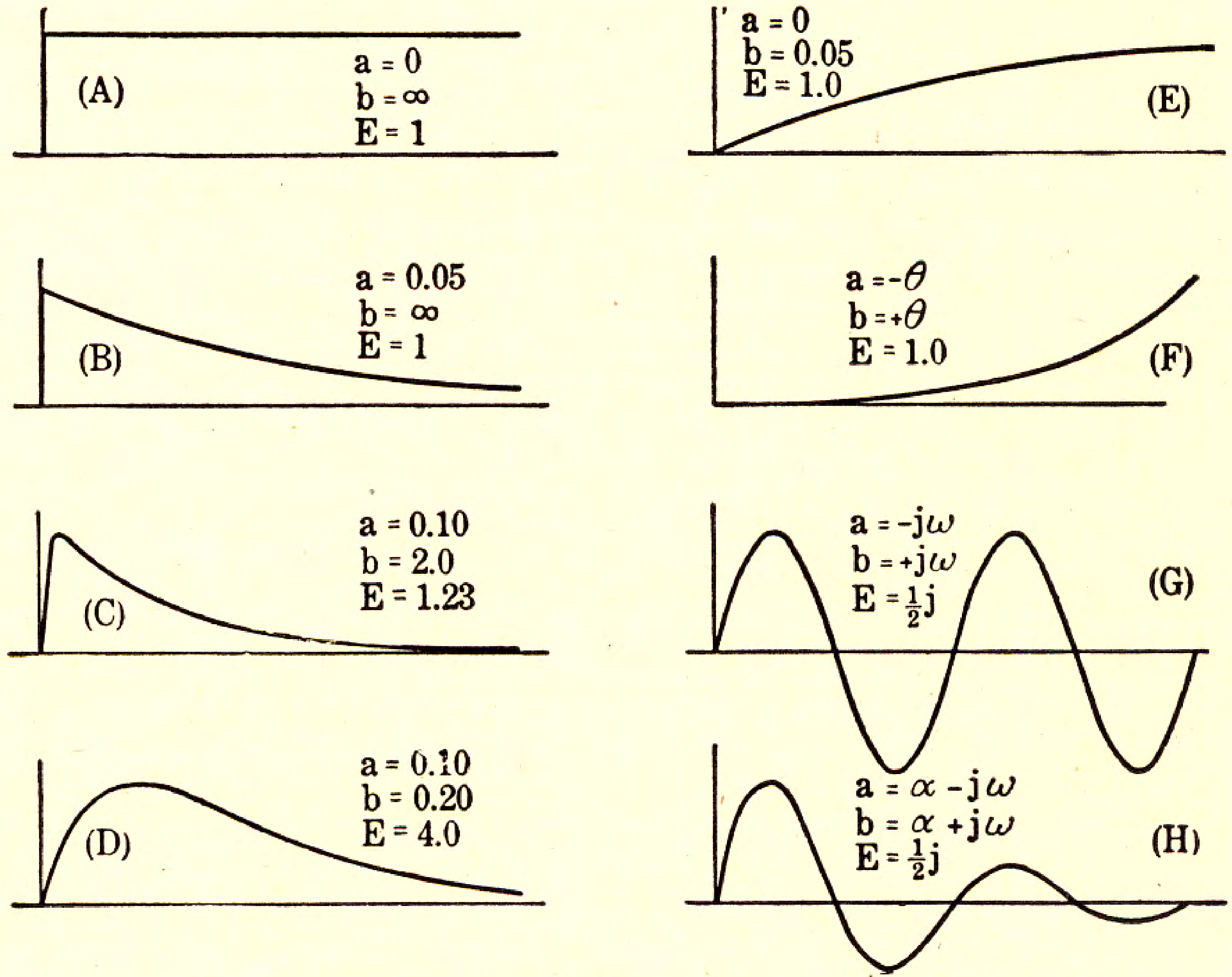


FIG. 4.—Empirical Wave Shapes Given by

$$e = E\,(\varepsilon^{-at} - \varepsilon^{-bt})$$

TRANSIENT OSCILLATIONS IN THE PRIMARY WINDINGS *

Numerical calculations covering practical cases, based on the analysis given in the previous chapter, show that the essential characteristics of the oscillations in the primary winding are substantially the same as obtain when the secondary winding is ignored, provided that the Fourier expansion is on the same base in both cases. It is appropriate, therefore, to give the analysis for a single independent winding, because the equations then become greatly simplified and easy to visualize, and a number of characteristic curves can be prepared. It must be borne in mind, however, that it may be necessary to make arbitrary changes in the circuit constants, particularly of the inductance coefficient, to obtain accurate numerical agreement. Also, the minor frequency set disappears in the single-winding theory, and there is no explicit indication of the effect of the secondary in fixing the appropriate Fourier expansion.

The following analysis is along the same lines as that given for the two-winding theory, and is idealized to the same extent, but the effect of the losses and of the applied wave shape is taken into account, and the influence of each of the several circuit constants is discussed. As before, the derivations are restricted to either a grounded or isolated neutral.

THE GENERAL DIFFERENTIAL EQUATION

Referring to Fig. 103*A*, the circuit constants per unit length of winding are:

L = inductance coefficient, including the partial interlinkages.
$M(x, y)$ = mutual inductance between elements at x and y.
C = shunt capacitance to ground.
K = series capacitance along the winding.
G = shunt conductance to ground.

g = shunt inductance along the winding.
r = series resistance.
n = turns.

The variables involved at any point of the winding are:

e = potential to ground.
i_1 = current in series capacitance K.
i_2 = current in the inductance L.
i_3 = current in the shunt conductance g.
i_4 = current to ground through G and C.
ϕ = total flux linkages at a point.
B = flux density.
t = time.
$p = \partial/\partial t$ = partial derivative with respect to time.
x, y = points along the winding, measured from the neutral end.
l = length of the winding.
$(m\,l\,t)$ = mean length of turn.
$2\,h$ = length of the leakage path.

The fundamental relationships are:

$$i_1 = K \frac{\partial^2 e}{\partial x \, \partial t} \tag{1}$$

$$i_3 = g \frac{\partial e}{\partial x} \tag{2}$$

$$i_4 = \left(G + C \frac{\partial}{\partial t}\right) e = \frac{\partial}{\partial x} (i_1 + i_2 + i_3) \tag{3}$$

$$\frac{\partial e}{\partial x} = r\, i_2 + \frac{n}{10^8} \frac{\partial \phi}{\partial t} \tag{4a}$$

$$= r\, i_2 + \frac{\partial}{\partial t} \int_0^l M\,(x, y)\; i_2\,(y) \cdot d\,y \tag{4b}$$

$$= r\, i_2 + \frac{\partial}{\partial t} \Big\{ L'\, i_2\,(x)$$

$$+ \int_0^l M\,(x, y)\,[i_2\,(y) - i_2\,(x)]\, d\,y \Big\} \tag{4c}$$

where

$$L' = \int_0^l M\,(x, y)\, d\,y = \text{self inductance}$$

and as in (2) of Chapter XII

$$\phi = \phi_m + \phi_l = \phi_m + \frac{0.4\,\pi\,(m\,l\,t)\,n}{h} \int_0^x \int_x^l i_2\,dy\,dz \tag{5}$$

where

ϕ_m = flux mutual to the entire winding.

ϕ_l = flux due to partial interlinkages.

From (4*a*) and (5)

$$\begin{aligned}\frac{\partial^4 e}{\partial x^4} &= r\,\frac{\partial^3 i_2}{\partial x^3} - \frac{0.4\,\pi\,n^2\,(m\,l\,t)}{h\,10^8}\,\frac{\partial^2 i_2}{\partial x\,\partial t} \\ &= r\,\frac{\partial^3 i_2}{\partial x^3} - \frac{L}{l^3}\,\frac{\partial^2 i_2}{\partial x\,\partial t}\end{aligned} \tag{6}$$

where

$$L = \frac{0.4\,\pi\,n^2\,l^3\,(m\,l\,t)}{h\,10^8} = \text{effective inductance}$$

By (1), (2), and (3) there is

$$\begin{aligned}\frac{L}{l^3}\,\frac{\partial^2 i_2}{\partial x\,\partial t} &= \frac{L}{l^3}\left(G + C\,\frac{\partial}{\partial t}\right)\frac{\partial e}{\partial t} - \frac{L}{l^3}\,\frac{\partial^2 i_1}{\partial x\,\partial t} - \frac{L}{l^3}\,\frac{\partial^2 i_3}{\partial x\,\partial t} \\ &= \frac{L}{l^3}\,G\,\frac{\partial e}{\partial t} + \frac{L}{l^3}\,C\,\frac{\partial^2 e}{\partial t^2} - \frac{L}{l^3}\,K\,\frac{\partial^4 e}{\partial x^2\,\partial t^2} - g\,\frac{L}{l^3}\,\frac{\partial^3 e}{\partial x^2\,\partial t}\end{aligned} \tag{7}$$

and

$$r\,\frac{\partial^3 i_2}{\partial x^3} = r\,G\,\frac{\partial^2 e}{\partial x^2} + r\,C\,\frac{\partial^3 e}{\partial x^2\,\partial t} - r\,K\,\frac{\partial^5 e}{\partial x^4\,\partial t} - g\,r\,\frac{\partial^4 e}{\partial x^4} \tag{8}$$

Substituting (7) and (8) in (6), there results

$$r\,K\,\frac{\partial^5 e}{\partial x^4\,\partial t} + (1 + g\,r)\,\frac{\partial^4 e}{\partial x^4} - \frac{L}{l^3}\,K\,\frac{\partial^4 e}{\partial x^2\,\partial t^2}$$

$$- \left(r\,C + g\,\frac{L}{l^3}\right)\frac{\partial^3 e}{\partial x^2\,\partial t} - r\,G\,\frac{\partial^2 e}{\partial x^2} + \frac{L}{l^3}\,C\,\frac{\partial^2 e}{\partial t^2} + \frac{L}{l^3}\,G\,\frac{\partial e}{\partial t} = 0 \tag{9}$$

If the losses can be neglected, Equation (9) reduces to

$$\frac{\partial^4 e}{\partial x^4} - \frac{L\,K}{l^3}\,\frac{\partial^4 e}{\partial x^2\,\partial t^2} + \frac{L}{l^3}\,C\,\frac{\partial^2 e}{\partial t^2} = 0 \tag{10}$$

Hereafter it will be convenient to take $l = 1$.

The total current is, from (3)

$$(i_1 + i_2 + i_3) = \left(G + C\,\frac{\partial}{\partial t}\right)\int e\,d\,x \tag{11}$$

The solutions to these equations must satisfy

a. The differential equation.
b. The terminal conditions at $x = 0$ and $x = l$.
c. The initial distribution at $t = 0$.
d. The final distribution at $t = \infty$.

If the solution corresponding to a constant sustained potential suddenly applied at $x = l$ can be found, then the solution for any other applied terminal voltage is given by Duhamel's theorem. The usual procedure in solving a partial differential equation is to assume the form of the solution and try it by direct substitution in the differential equation and the boundary conditions. Each tentative trial usually suggests the necessary changes and adjustments in order to meet the complete specifications. Therefore, in order to choose the proper solution from among the infinite number of functions which will satisfy the differential equations, it is necessary to first investigate the boundary conditions.

3) Marconi Aerial Dimensions:

Upon the configuration of supporting masts, the Marconi wireless company erected the first electrostatic aerial to be seen at Bolinas. The structure was basic, consisting of 32 lines, evenly spaced, running longitudinal from the powerhouse to the aerial terminus. Each line consisted of a bronze wire rope of about ½ inch diameter. A partially buried section is to be found at the terminal row (fig 8-41). This cable is woven with 20 gauge calcium bronze wires. The 32 lines fanned out from the main aerial anchor at the powerhouse (fig 8-27), rising to full height at mast row one. The 32 line mast row four ended upon a row of 32 auxiliary masts, the terminal row. Each auxiliary mast consisted of a 4-inch cast iron pipe set in a concrete block (fig 8-40). Photographs indicate the masts to be about 12 to 15 feet in height. A recent water project destroyed most of the terminal row, but several mast bases are still seen on the right-hand side of the aerial perimeter (fig 8-42). Interpolation of a 1940 aerial photograph shows 32 mast bases total made up this row, but only 24 can be accounted for (fig 8-4). The nature of this termination is unclear, but the absence of guy anchors in association with the row of auxiliary masts would indicate that each of the 32 bronze cables descended vertically, thus no lateral forces needed to be resolved with guy structures. Therefore it is assumed that the 32 lines formed a 90° angle at the line, 560 feet beyond mast row three, and the aerial was thus folded, ending at near ground level upon the terminal masts.

4) Aerial Electric Constants:

The operating frequency of the disruptive discharge oscillator delivering excitation to the aerial-ground system is given at 44.77 kilocycles per second. The electromagnetic wavelength is thus 21 thousand feet. The length of aerial from the building end downleads, to the point of aerial termination, is 3000 feet. The ratio is thereby close to 0.16 to 1, a little over one-eighth wavelength. The downward section of the termination, consisting of the 32 downleads, constitutes a terminal condenser, and the aerial, an eighth wave stripline transformer. Thus the electrostatic capacity of the termination would appear as a resistance at the powerhouse end. The electrostatic capacity of the aerial-ground structure, as defined by its physical dimensions, is calculated as:

$C_o = 32000$ micro-micro-farads.

And, as given by many sources, the electrostatic potential of the wireless aerials of Bolinas was 100 thousand volts, and thus the electrostatic power flow is:

$P_o = 150$ megavolt amperes,

...at a current of 1½ thousand amperes. This is a Titanic quantity of electricity. The electrostatic capacity of the aerial-ground confined region is given as:

$C_c = 25000$ micro-micro-farads.

This is the electricity sandwiched between the underside of the aerial and the surface of the ground structure beneath it. This electricity is of no use in the transmission process, but represents a useless surging. The electrostatic capacity of the upper surface of the aerial out to free space is estimated as:

$K_s = 7000$ micro-micro-farads.

This gives a displacement current into space of 500 amperes and thus an electrostatic power flow of:

$P_s = 50$ megawatts,

...this power representing the transmission of electric force into space, because the aerial operates in phase opposition to the ground structure. The bottom surface of the ground system sends a current of equal magnitude to the space current, that is, 500 amperes of current are transmitted into the earth's interior:

Arial Electric Constants

$I_s = 500$ amperes.

The energy required by the aerial ground is equal to that delivered by the disruptive discharge oscillator which has been established to be:

$W_o = 300$ kilowatts.

Since the stripline configuration of the aerial parallel to ground represents a section of transmission line of:

$Z_c = 75$ ohm.

And of electrical length approximately one-eighth, it is:

$R_t = Z_T$

That is, the electrostatic capacity of the aerial-ground sandwich does not appear at the aerial input, but the reactance of the aerial terminus appears as a resistance to the oscillator, providing the required energy. Hereby the oscillator delivers its electrostatic power to the displacement current and that power confined appears as a leakage of electrical energy. This would appear as the Marconi wireless design principle.

The Marconi electrostatic aerial was determined by Marconi to be directive in a direction longitudinal with the axis. According to electromagnetic principles, no such directivity would exist. The aerial would transmit in all directions. However, the Marconi aerial is a low impedance section of transmission line, incapable of electromagnetic radiation. The electrostatic wave of propagation along the free space portion of the aerial is about 1½ times faster than the electromagnetic velocity of light. Through the experiments of Marconi (fig. 13), the electrostatic wave is launched longitudinal with respect to the aerial axis and in a distance much shorter than a wavelength. The free space velocity is given by the relation:

$$\sqrt{C/K} = V_o / V_c = \Upsilon^{-1}.$$

That is, the ratio of velocities squared is equal to the ratio of electrostatic (dielectric) capacities by substitution:

$$\Upsilon^2 = 2.17$$

...and the free-space wave velocity is thus:

$\Upsilon = 1.5$ times the velocity of light.

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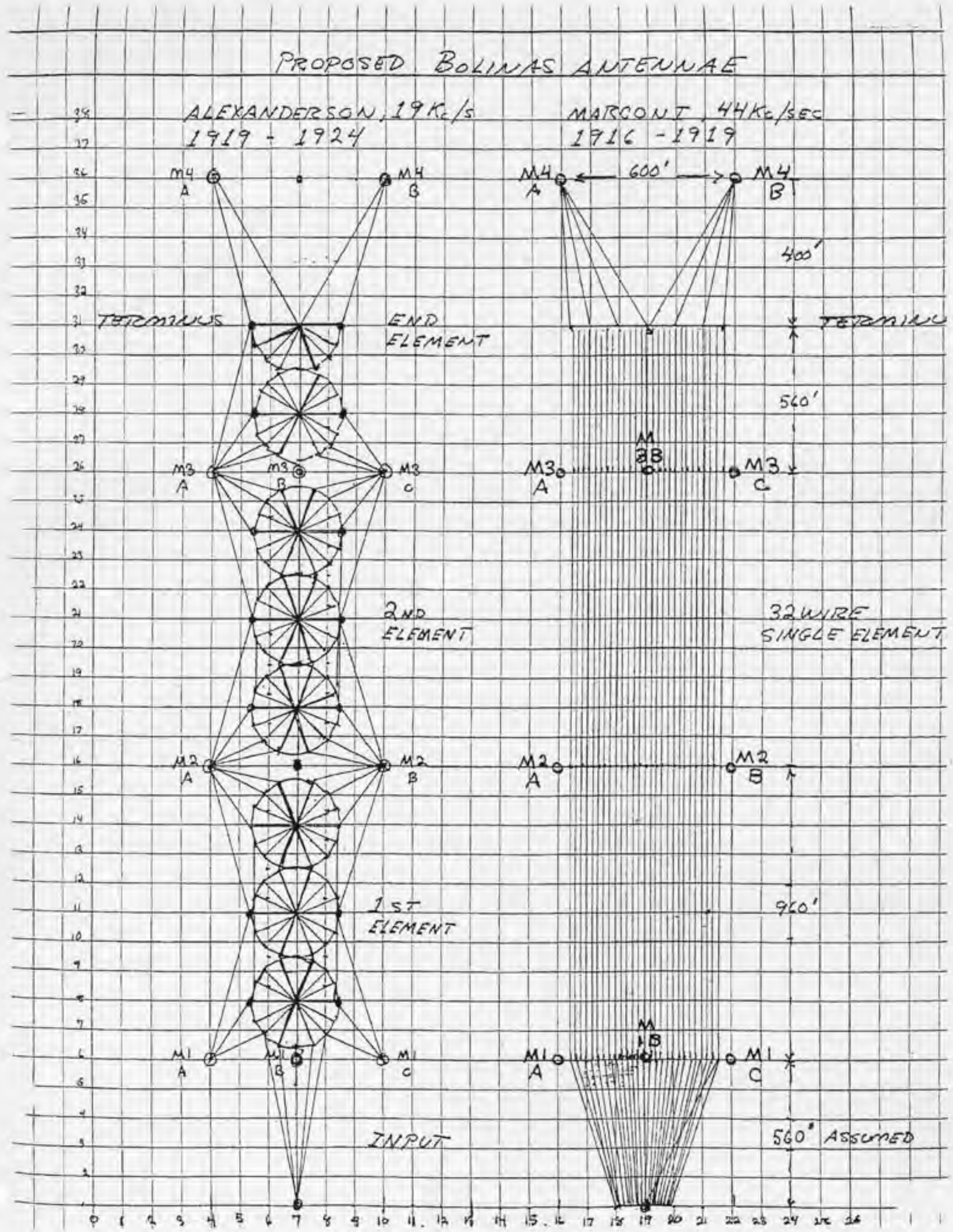
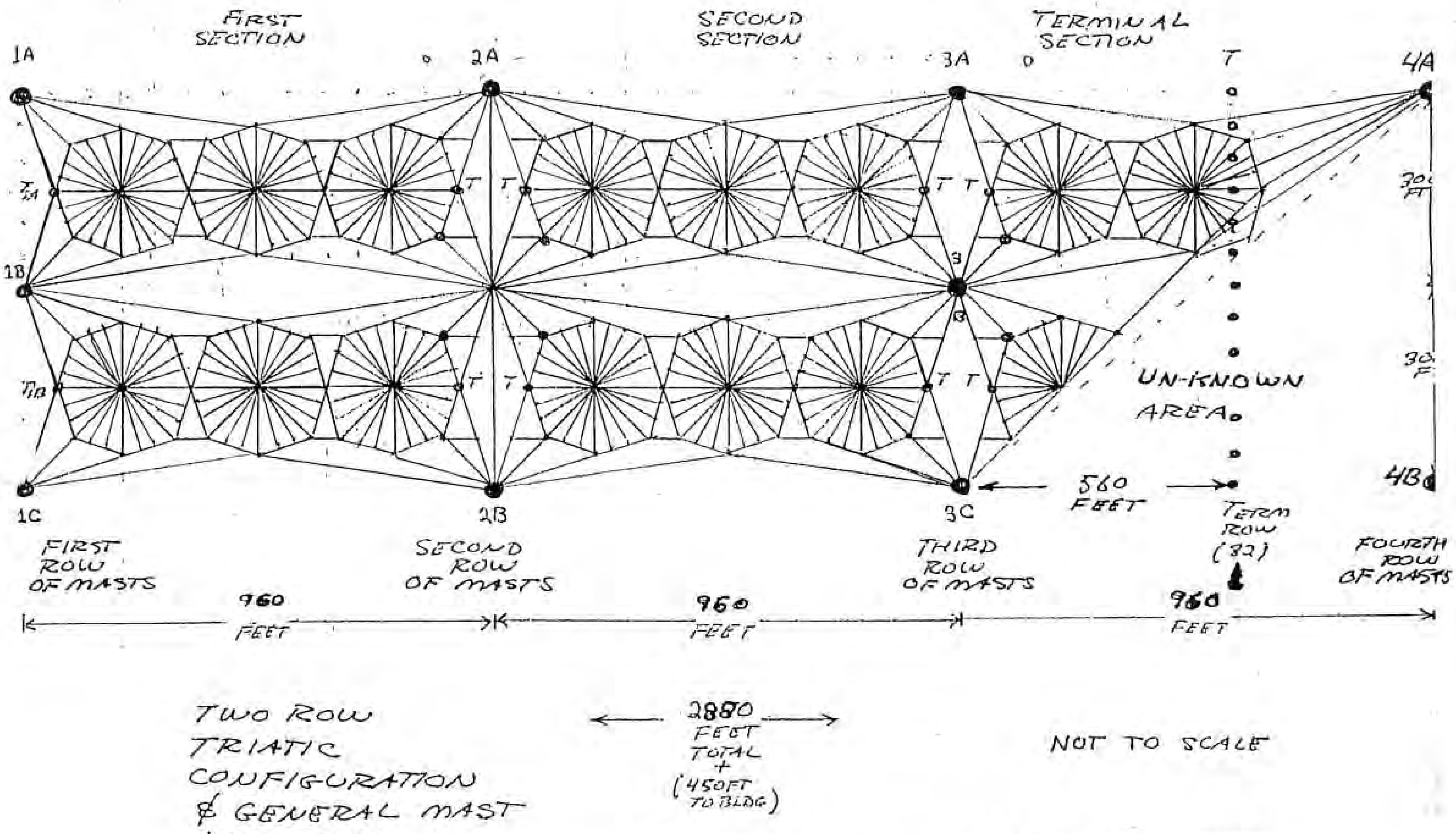
From the physical dimensions of the Marconi wireless electrostatic aerial, through the use of standard radio formulae as given by the R.C.A. handbook: "Radiotron Designers' Handbook," and by Frederick Terman in his "Radio Engineers' Handbook" (Stanford University), the electrical constants have been determined.



8-2 Marconi Layout, 1916-1919 (44 Kc/sec.)

8-3 Alexanderson Layout, 1919-1924 (19 Kc/sec.)

Antenna Diagram



8-4 Two-row Triatic Configuration and General Mast Location

Marconi's Directive Antenna. — In 1906 Mr. Marconi presented to the Royal Society an account of some experiments which showed that an antenna having a short vertical part and then extending away to a considerable distance in a horizontal direction, as shown in Fig. 210, emitted electric waves most strongly in the direction D away from which the free end of the antenna points.

FIG. 210. Marconi's directive antenna.

Marconi's experiments showed for a given distance between the receiving station and the transmitting station the relative intensities in different directions which, plotted in polar coördinates, give a curve of the form of Fig. 211. In this figure the relative intensities in different directions are the lengths of the radii drawn from the origin to the curve.

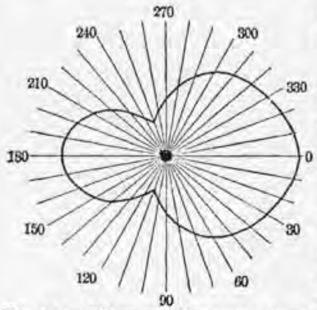
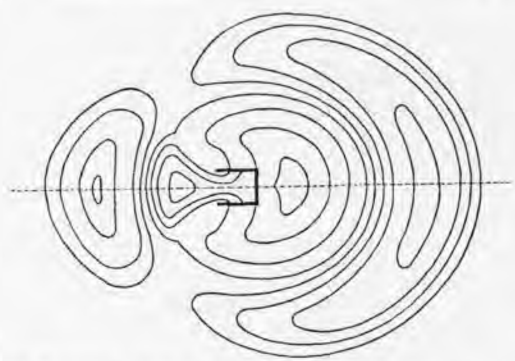


FIG. 211. Diagram of intensity about Marconi's directed antenna.

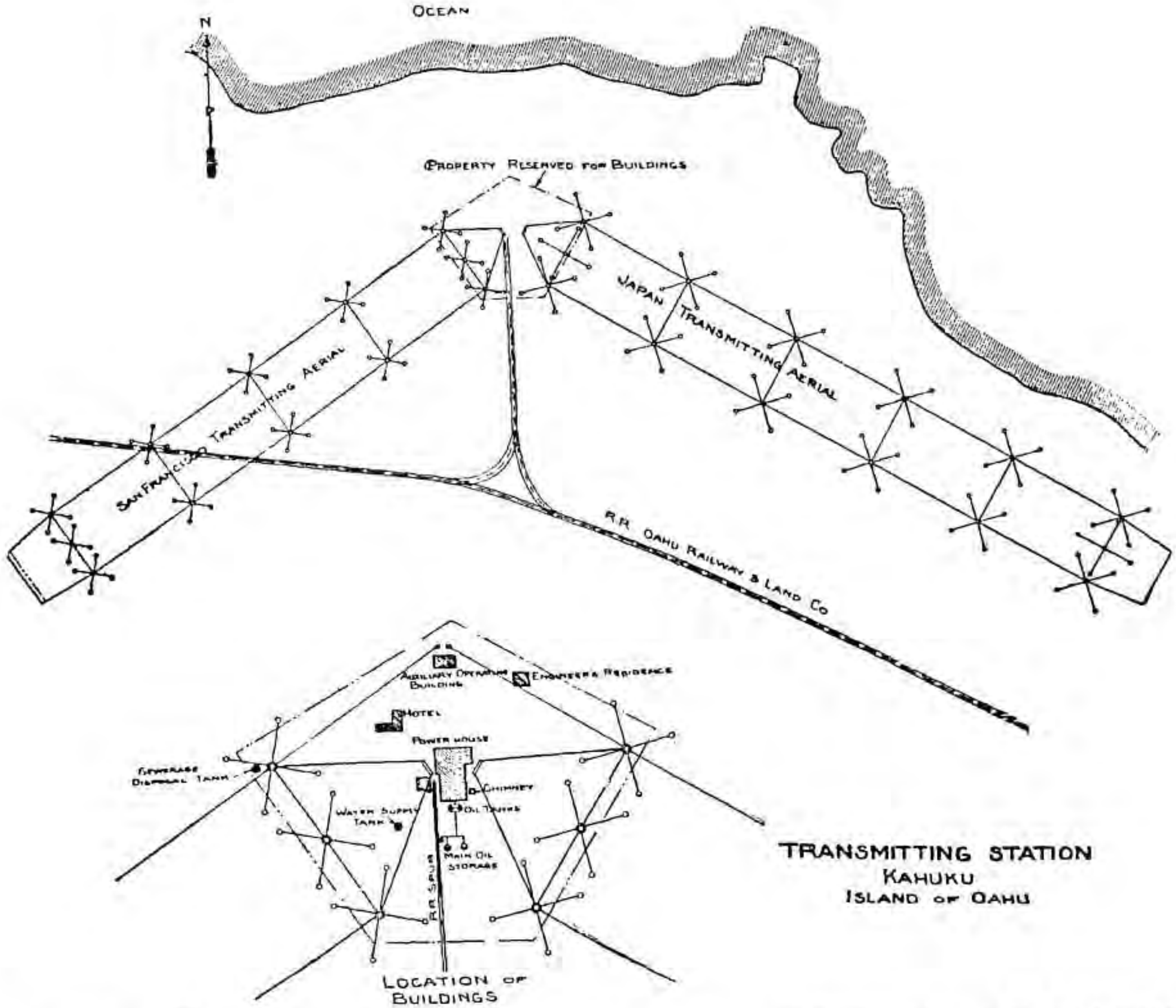
In like manner a receiving antenna consisting of a short vertical part and a long horizontal part receives more strongly waves arriving from the direction away from which the open end of the antenna points. Mr. Marconi has utilized this principle in the construction of his powerful stations at Wellfleet and at Poldhu.

8-6 Marconi's Directive Antenna (1906). Review article



8-7 Dr. Uller's Diagram of Field of Electric Force about the Bent Antenna

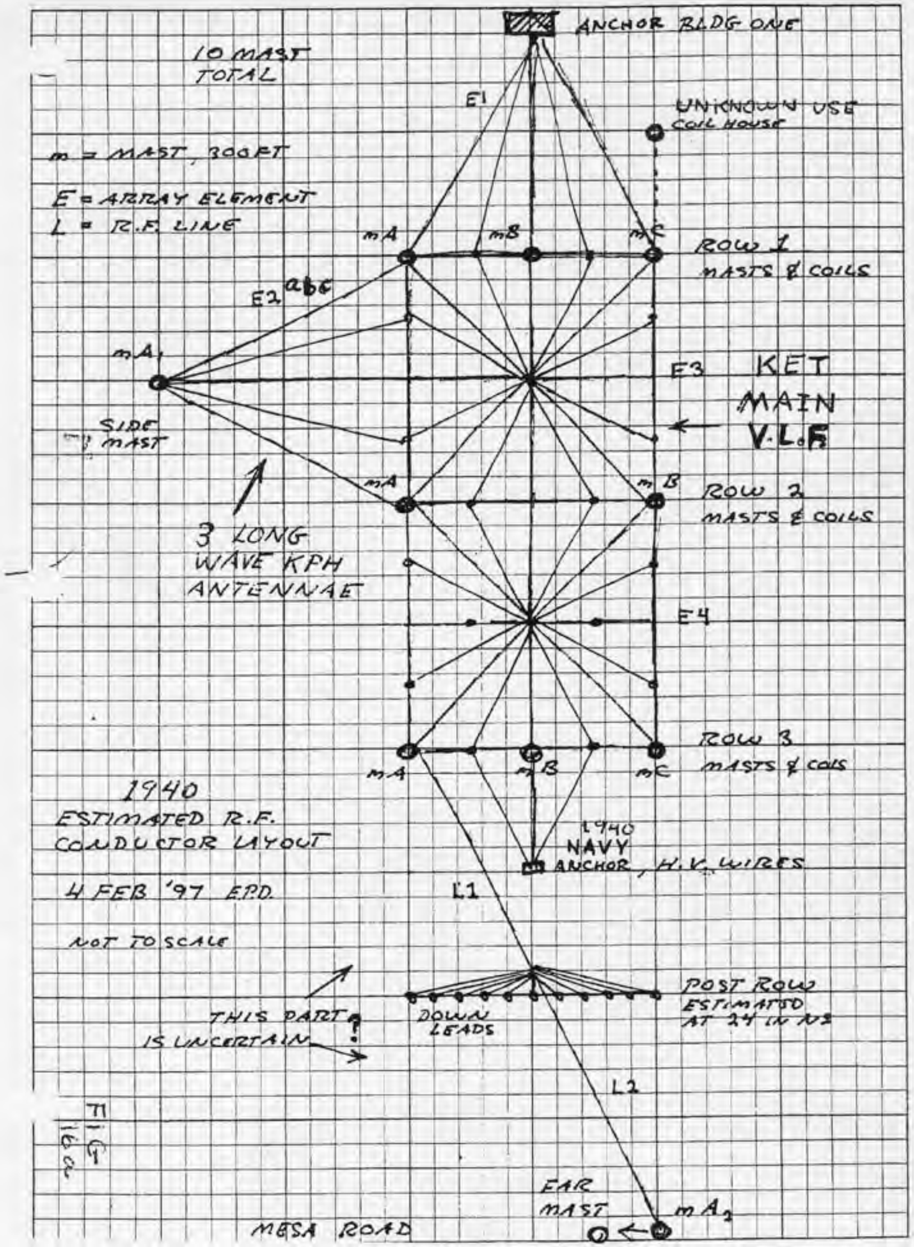
Marconi's Directive Antenna



8-15 Plan of Transmitting Aerials at Marconi Station, Kahuku, Island of Oahu (Hawaii)

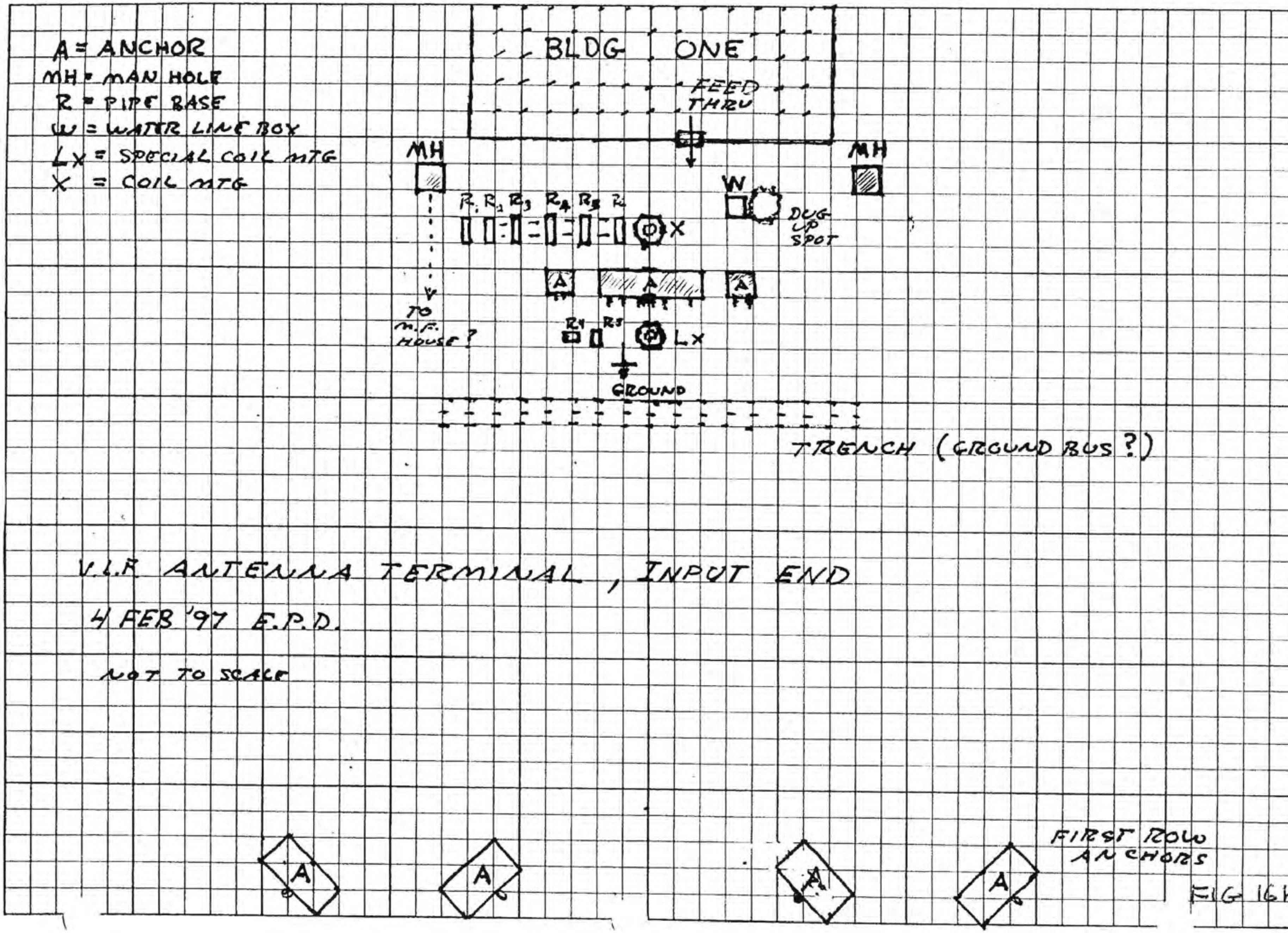
NOTICE TERMINAL
END OF AERIALS

1953



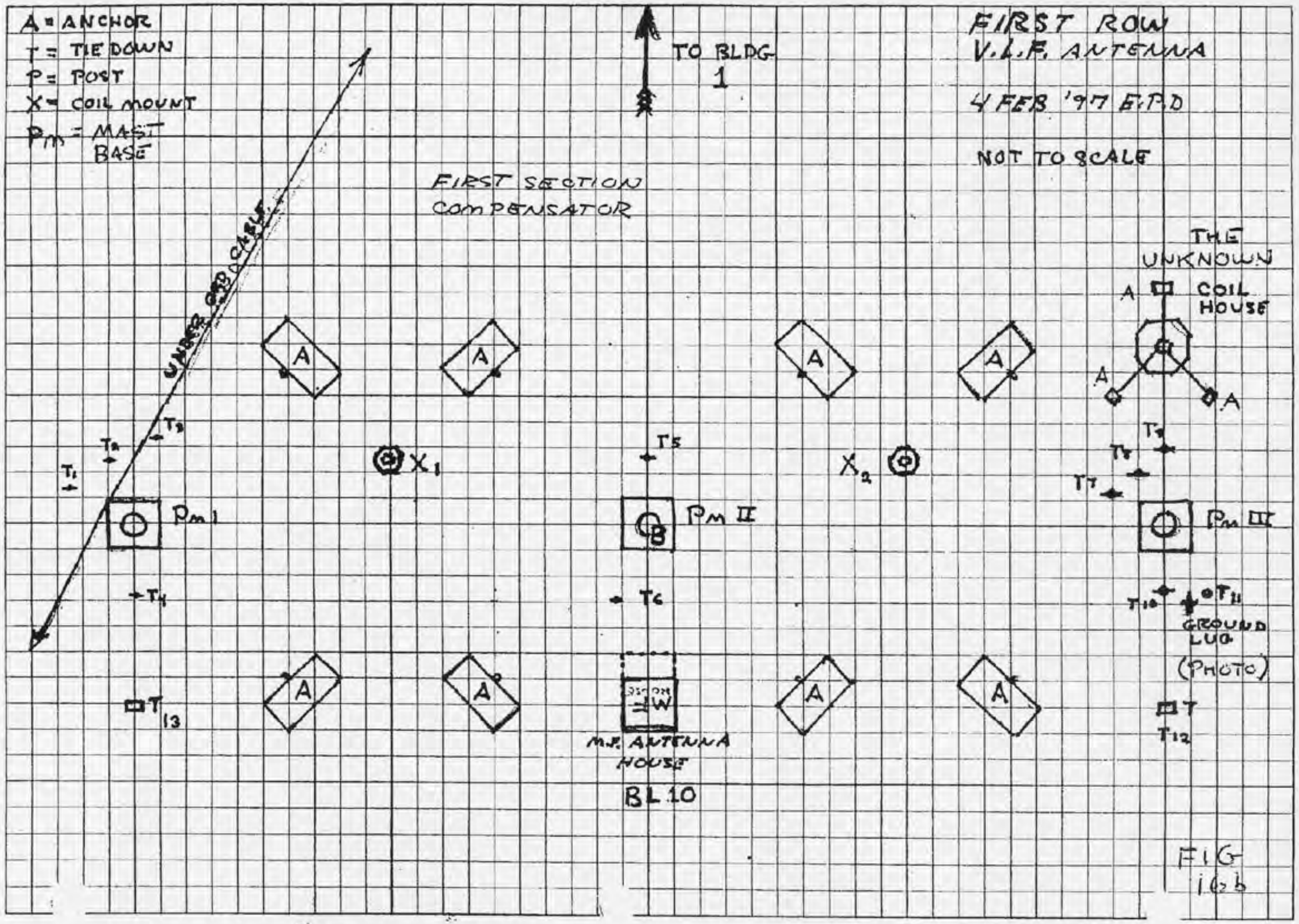
8-20 Estimated R.F. Conductor Layout, 1940 (EPD plan drawing #1).

Antenna Layout 1



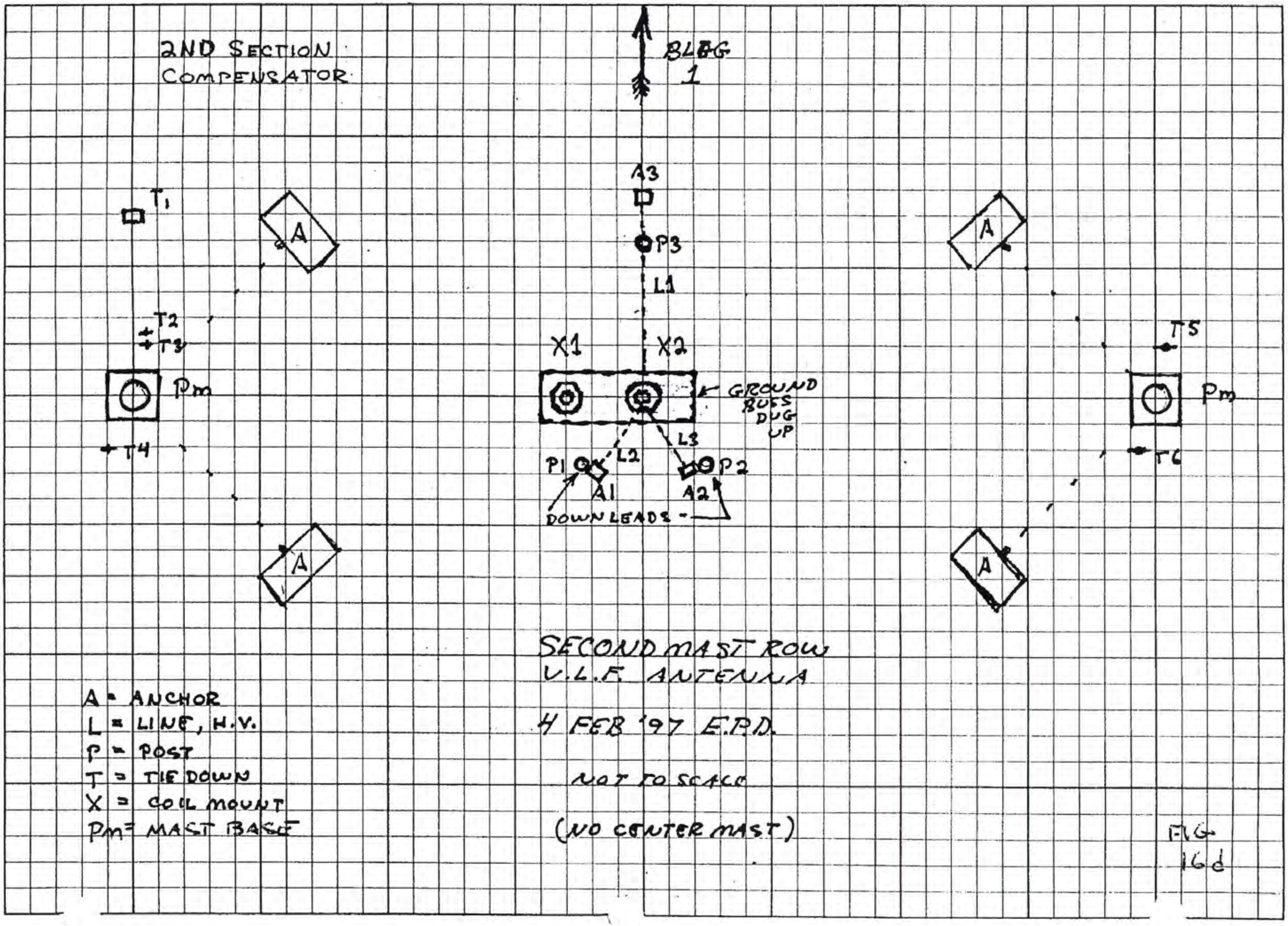
8-27 V.L.F. Antenna Terminal, Input End (EPD plan drawing #8)

86

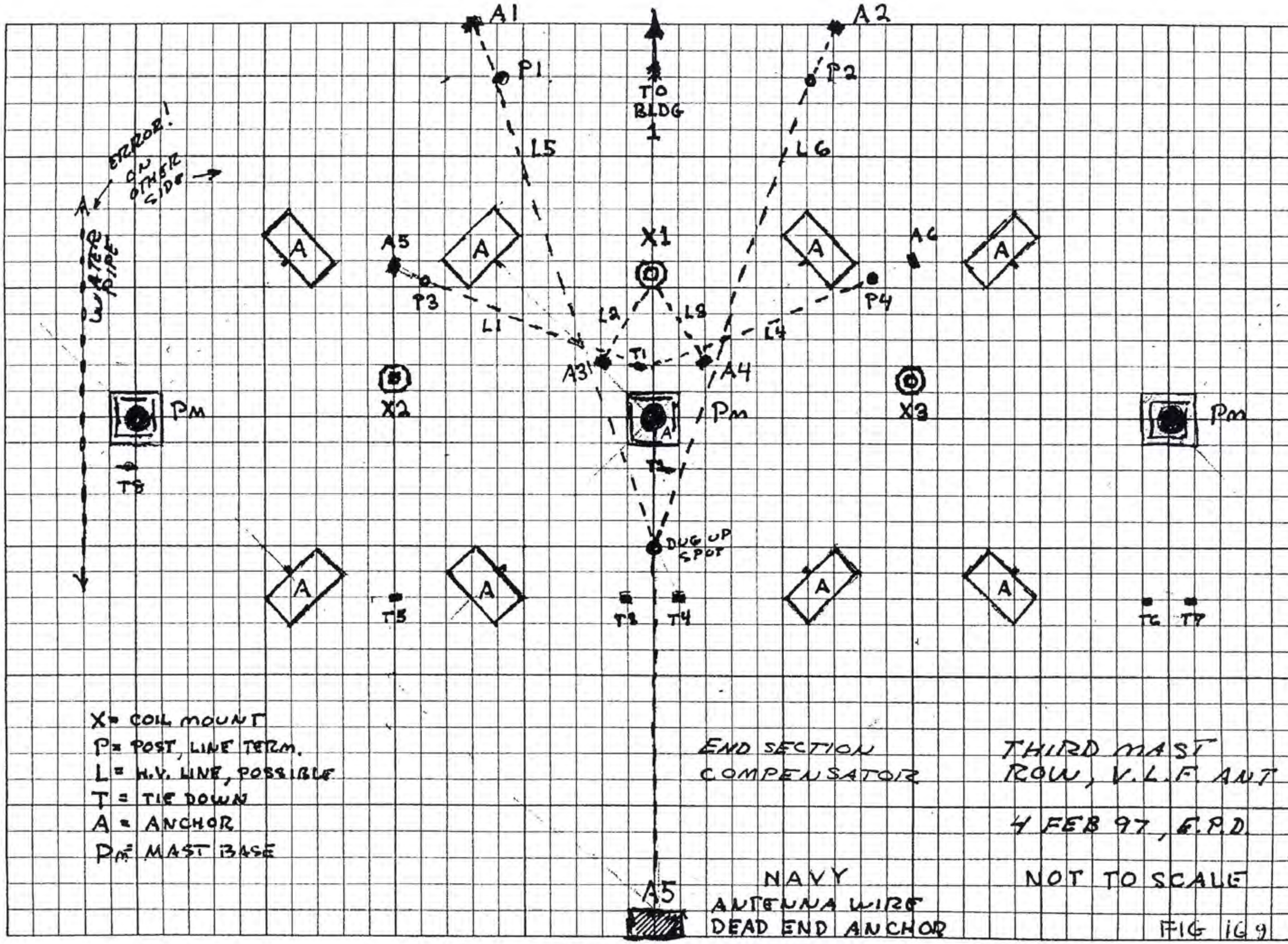


8-21 First Row V.L.F. Antenna (EPD plan drawing #2)

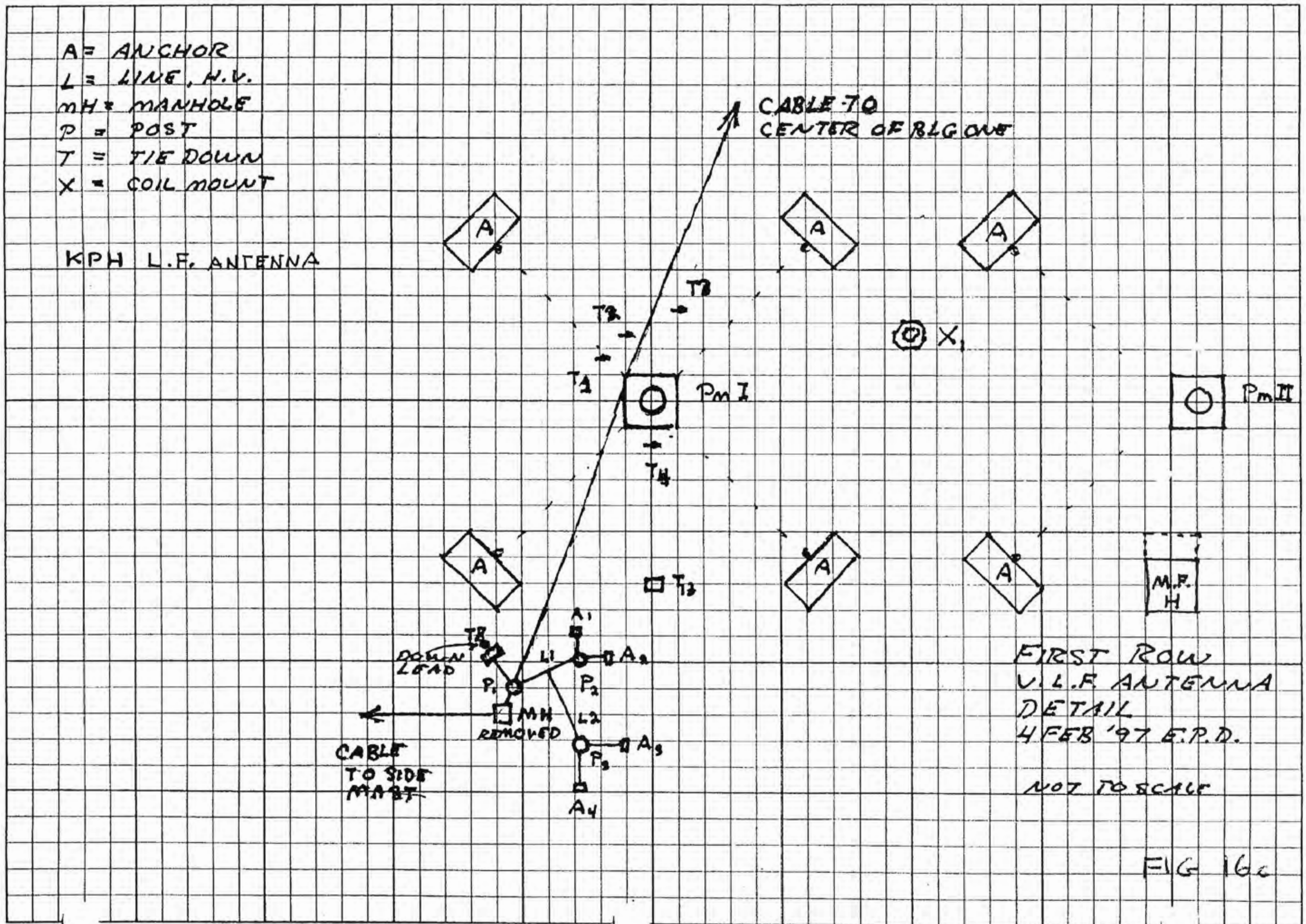
Antenna Layout 2



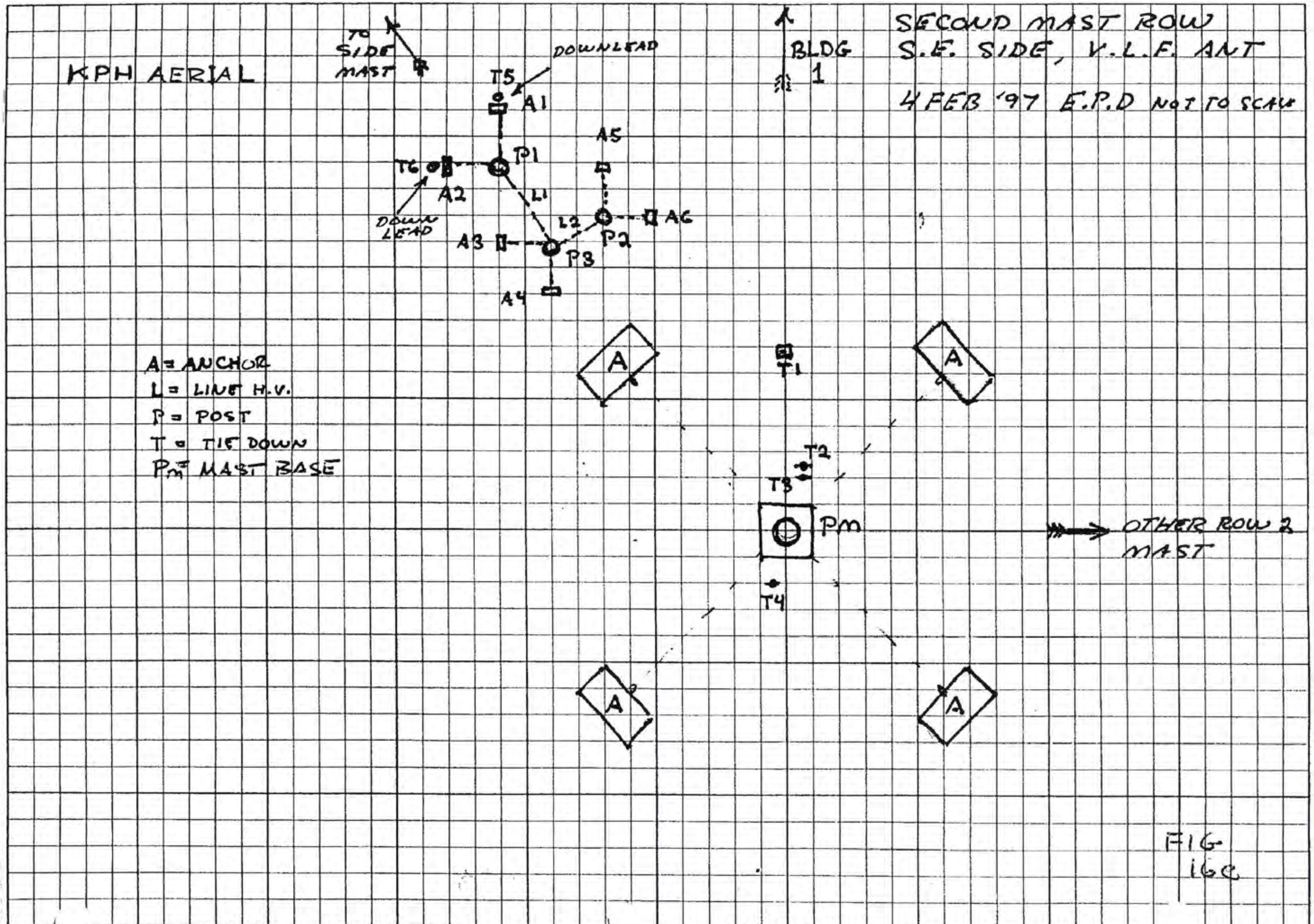
8-23 Second Mast Row V.L.F. Antenna (EPD plan drawing #4)



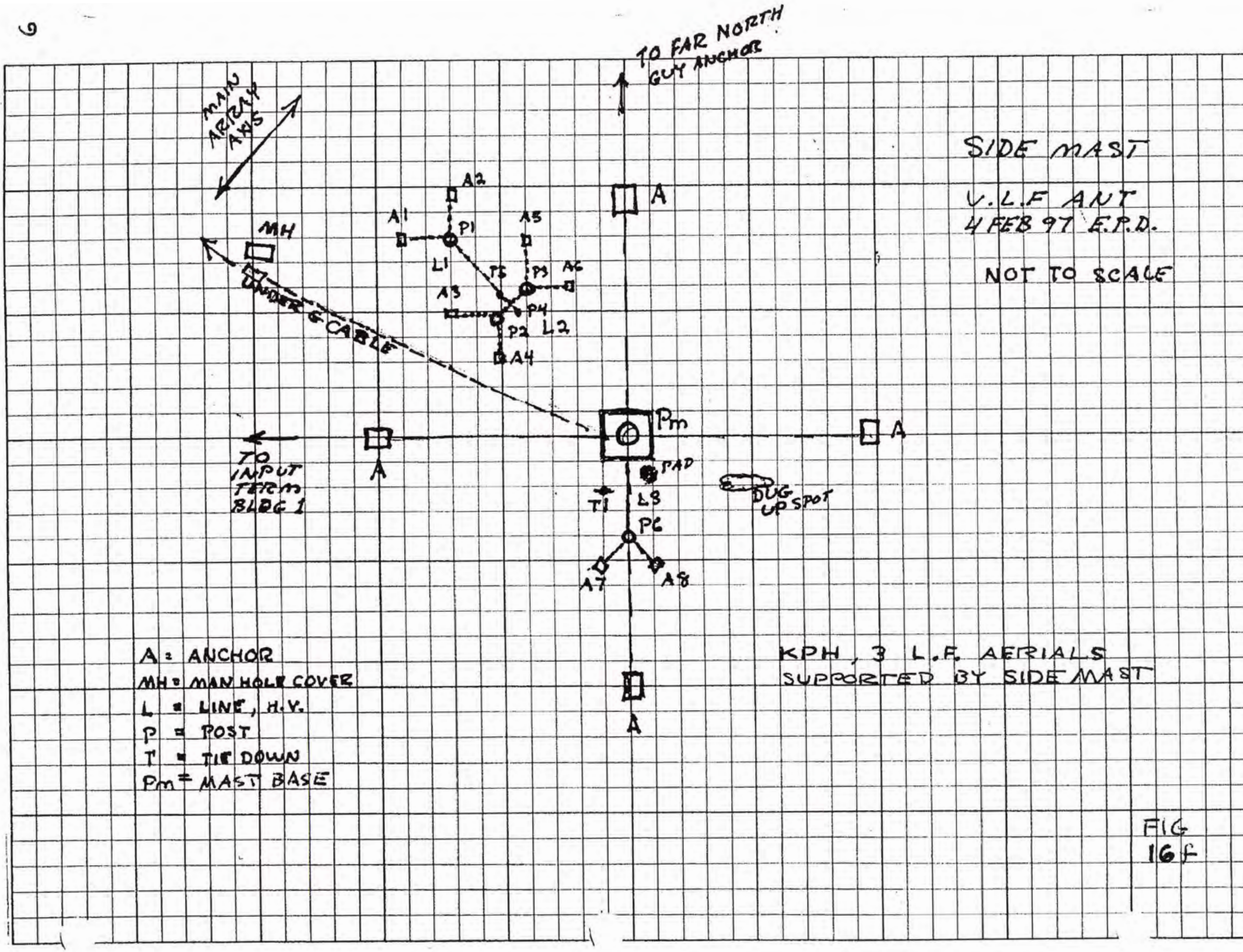
Third Mast Row, V.L.F. Antenna (EPD plan drawing #7)



First Row V.L.F. Antenna – Detail (EPD plan drawing #3)



8-24 Second Mast Row S.E. Side, V.L.F. Antenna (EPD plan dr. #5)



8-25 Side Mast, V.L.F. Antenna (EPD plan drawing #6)

I)

A) The electrostatic capacity of the Bolinas array can be divided into two distinct categories:

1) That part of the electrostatic field confined between the elevated capacity and the ground plane:

$C_c = 1.5 \times 10^{-8}$ farad 0.015 uFd

2) That part of the electrostatic field which extends from the elevated capacity to space:

$C_s = 3.5 \times 10^{-9}$ farad 3500 pFd.

And therefore a total electrostatic capacity of:

$C_o = 1.9 \times 10^{-8}$ farad

With a ratio of:

$C_s : C_c = 0.35.$

And a transmission efficiency of:

$C_s : C_o =$ 19 percent.

B) The electrostatic potential is given as:

$E_o = 100$ kilovolts.

With an angular velocity of:

1.2×10^5 radians per second.

Energy is supplied to this potential at a rate of:

$P = 200$ kilowatts.

Scale 1

C) For a peak potential of 100 kilovolts, the two electrostatic fields are:

1) The confined field:

$\Psi = 1.8 \times 10^{10}$ lines of force

$W = 32$ watt-second

2) And the transmitted field:

$\Psi = 4.2 \times 10^{9}$ lines of force

$W = 7$ watt-second

D) For potential variation of 1.2×10^{5} radians per second, the power flow of the two electrostatic fields are:

1) Confined power flow:

$P_c = 17 \times 10^{6}$ volt-amperes

$X_c = 6 \times 10^{2}$ sec. per farad (ohm)

2) And the transmitted power flow:

$P_s = 4.8 \times 10^{6}$ volt-amperes

$X_s = 2 \times 10^{3}$ sec. per farad (ohm)

E) The total electric current transmitted into the earth is hence given:

$I_o = 48$ amperes

With a transmission loss of 200 kilowatts and a corresponding electromotive force of:

$E_o = 4200$ volts

F) For the entire array the total power flow is:

Scale 2

$P = 21 \times 10^6$ volt-amperes

And for a dissipation rate of 200 kilowatts, the power multipaction factor is thus given:

$\varphi = 100 \times$ dimensionless

II) The entire array is divided into three distinct section elements: element 1 and element 2, and a third terminal element

A) The mid-section elements are of the following electrical dimensions:

1) Electrostatic capacity to space:

$C_s = 1.4 \times 10^{-9}$	farad	1400 pFd
$P_s = 1.7 \times 10^6$	volt-amperes	
$I_s = 17$	amperes	
$X_s = 6 \times 10^3$	sec. per farad	$6K\Omega$

2) Electrostatic capacity to ground:

$C_c = 4.9 \times 10^{-9}$	farad	4900 pFd
$P_c = 5.6 \times 10^6$	volt-amperes	
$I_c = 56$	amperes	
$X_c = 1.8 \times 10^3$	sec. per farad	$1.8K\Omega$

3) Electromagnetic inductance:

$L = 1.3 \times 10^{-4}$	Henry
$X_L = 16$	Henry/sec. (OHM)

4) The electro-motive force developed by the electromagnetic induction of the element half-section L/2 is given by the relation:

$E_\ell / I_T = X$ $E = 550$ volts

And therefore, the power flow of this induction:

$E_L \times I_T =$ $P = 40 \times 10^3$ volt-amperes

And thus the ratio of magnetic to electrostatic power flow is:

$P_L : P_O = 40:7300 =$ 1.5 percent

Scale 3

B) Having derived the electromagnetic and the electrostatic coefficients of the elemental sections, the electromagnetic propagation coefficients are thus:

Z_c = transmission impedance of confined electromagnetic wave
Z_c = 173 ohm
Z_s = transmission impedance of un-confined electromagnetic wave
Z_s = 316 ohm

And likewise:

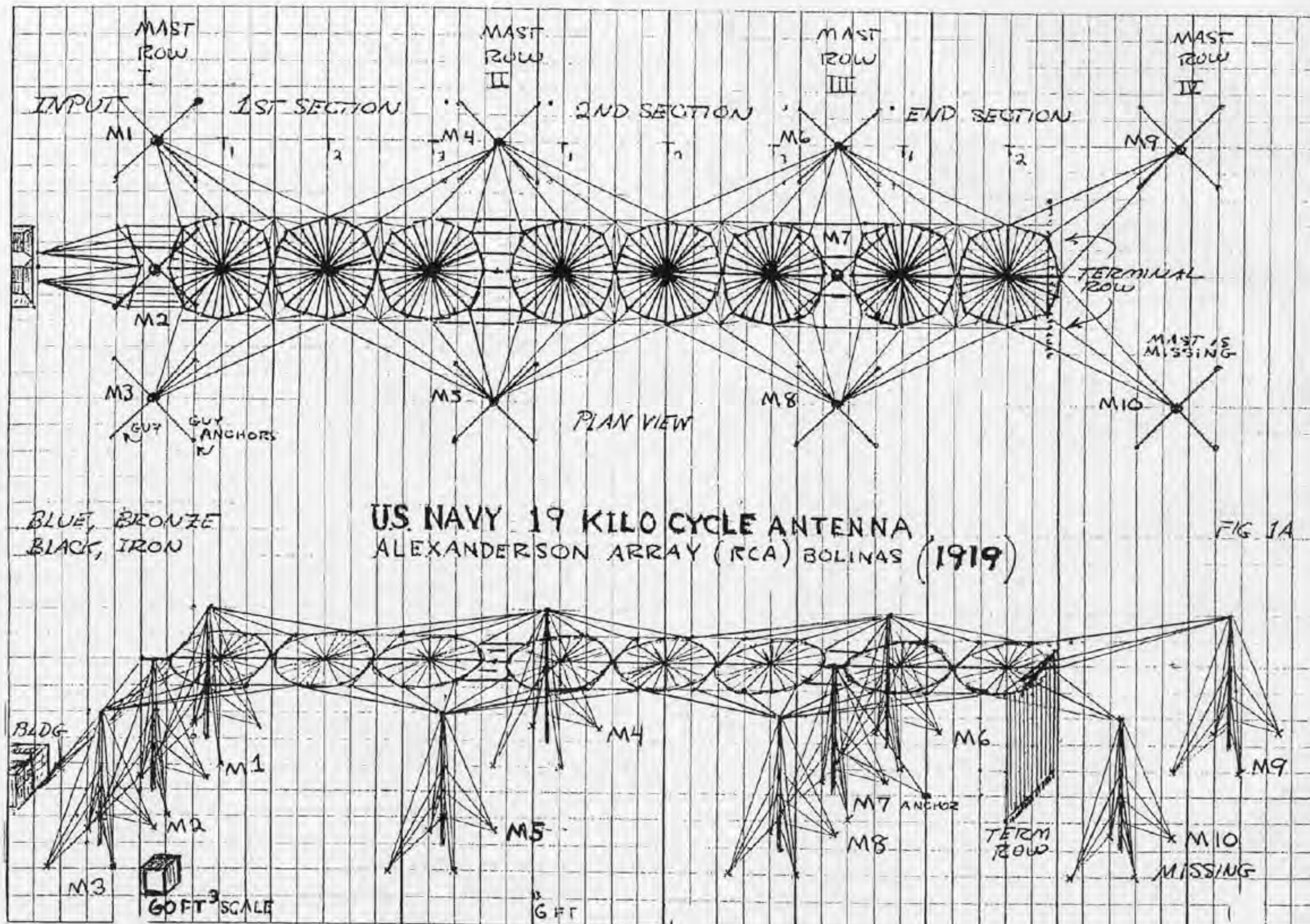
V_o = transmission velocity of confined propagation

$$V_o = 3 \times 10^{10} \quad \text{cm./sec.}$$

V_s = transmission velocity of un-confined propagation

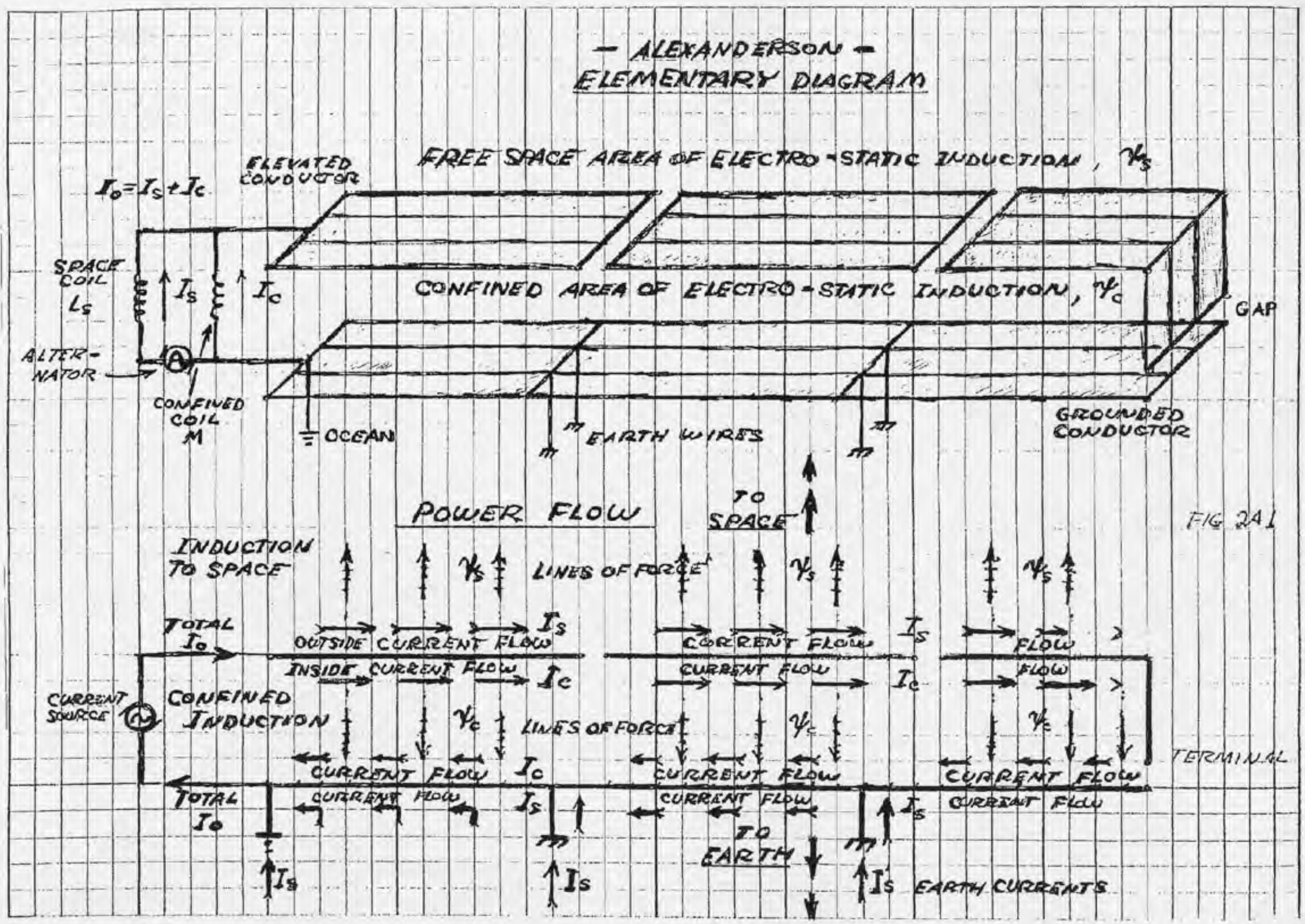
$$V_s = 5.6 \times 10^{10} \quad \text{cm./sec.}$$

9-1 U.S. Navy 19 Kilocycle Antenna. Alexanderson Array (R.C.A.), Bolinas, 1919

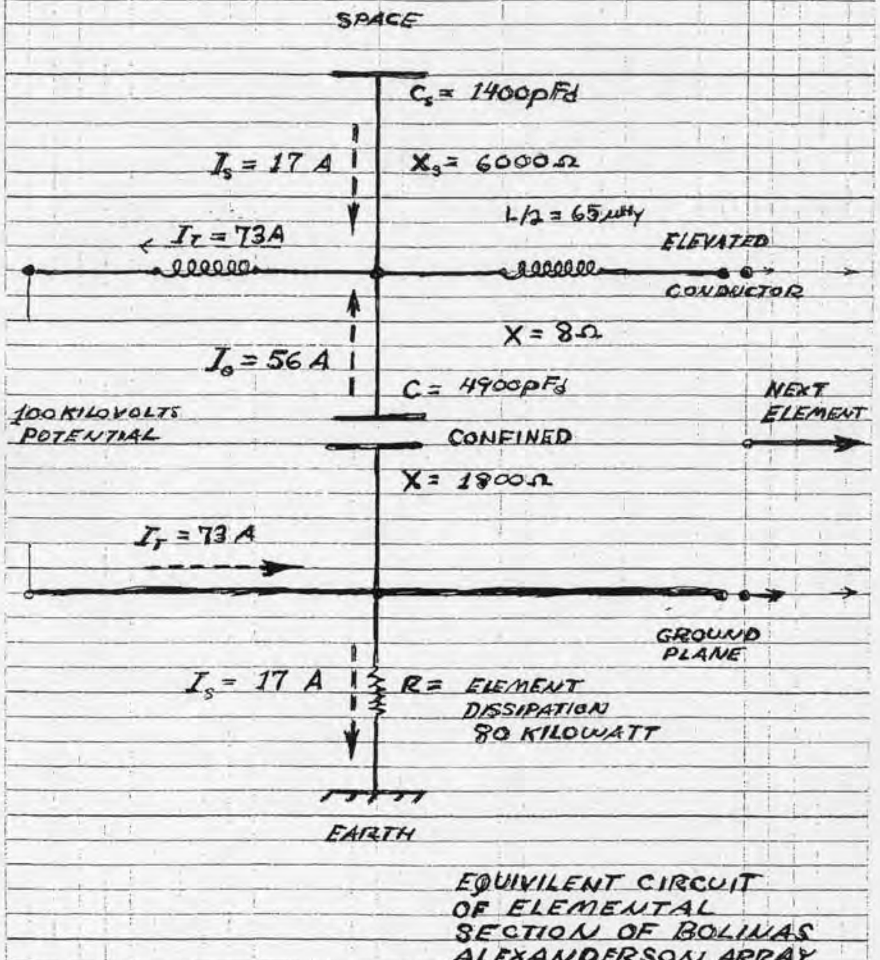


Bolinas Antenna

9-2 Alexanderson – Elementary Diagram

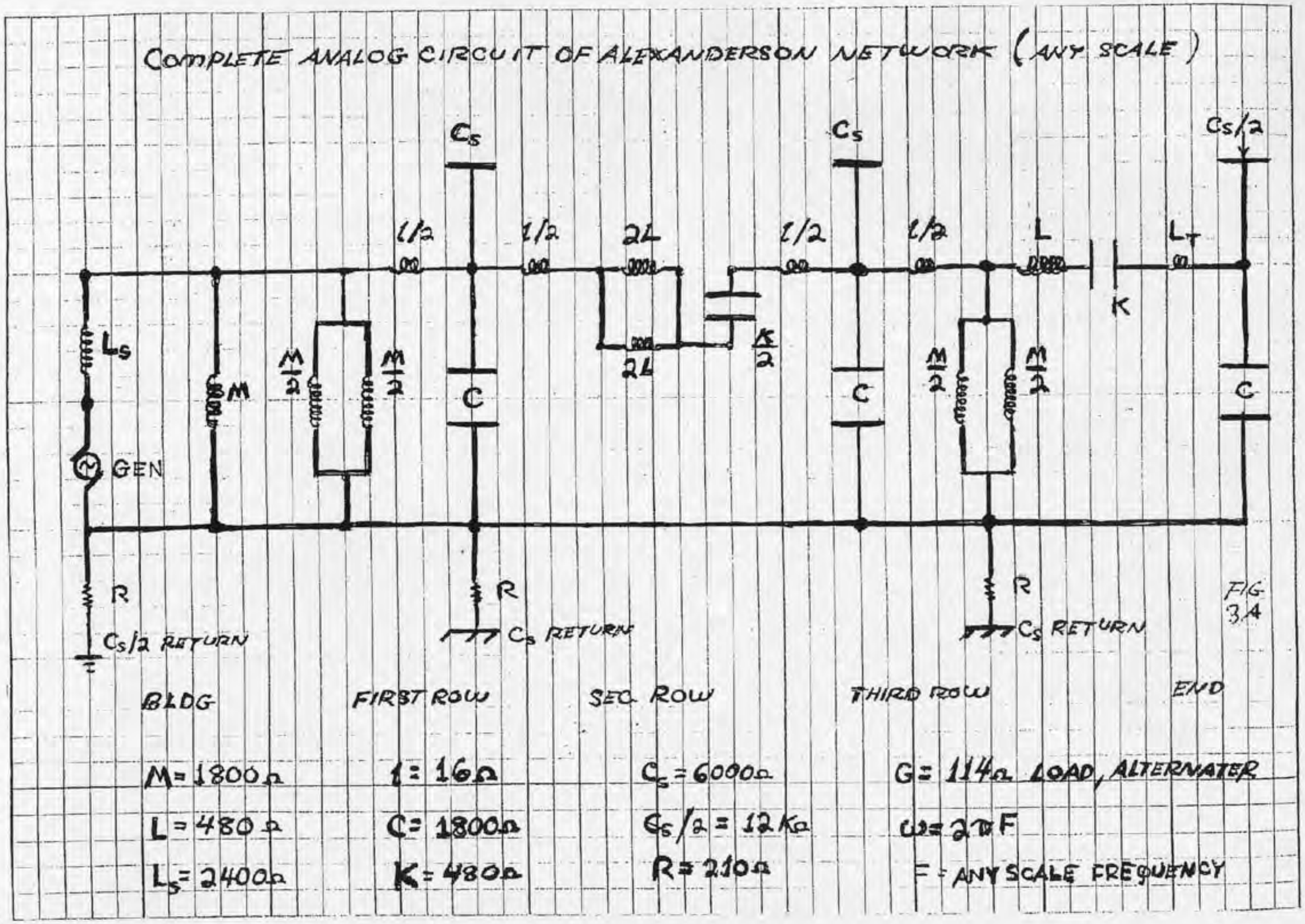


Antenna Schematic

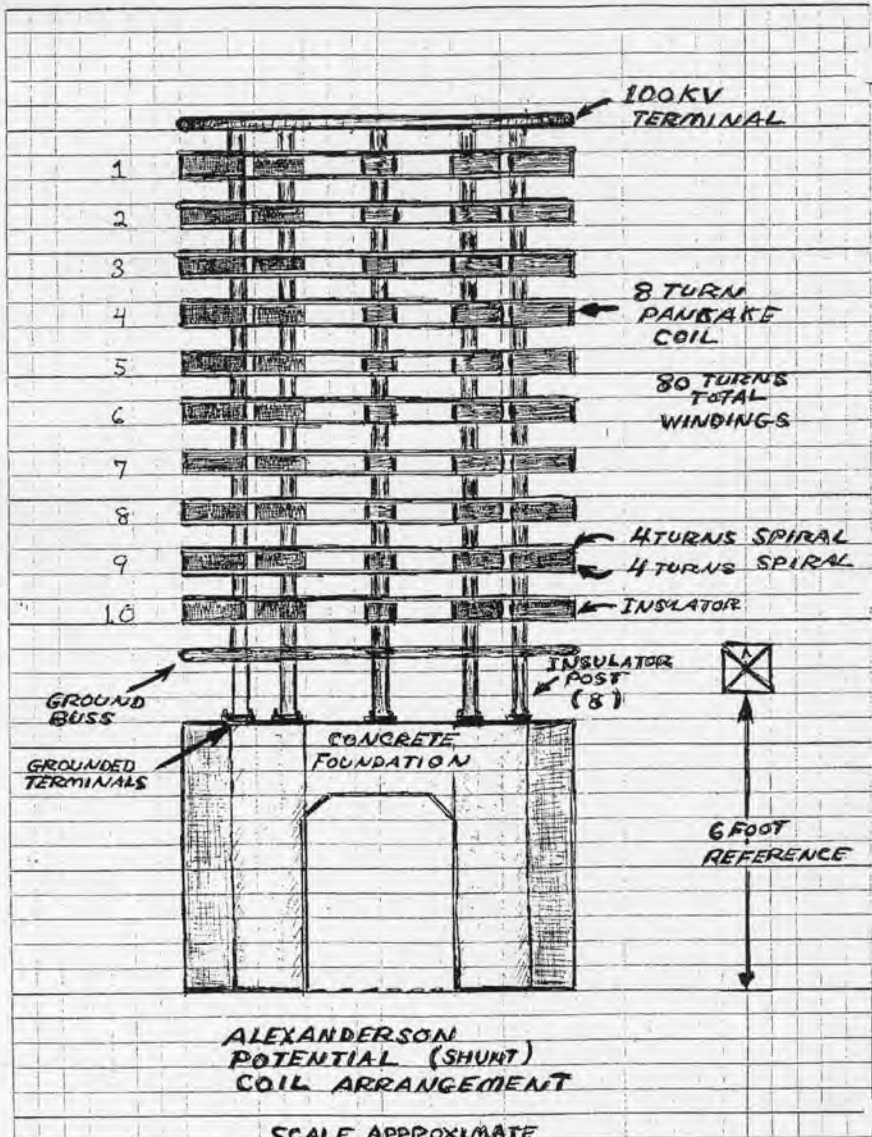


9-3 Equivalent Circuit of Elemental Section of Bolinas Alexanderson Array

9-4 Complete Analog Circuit of Alexanderson Network (any scale)

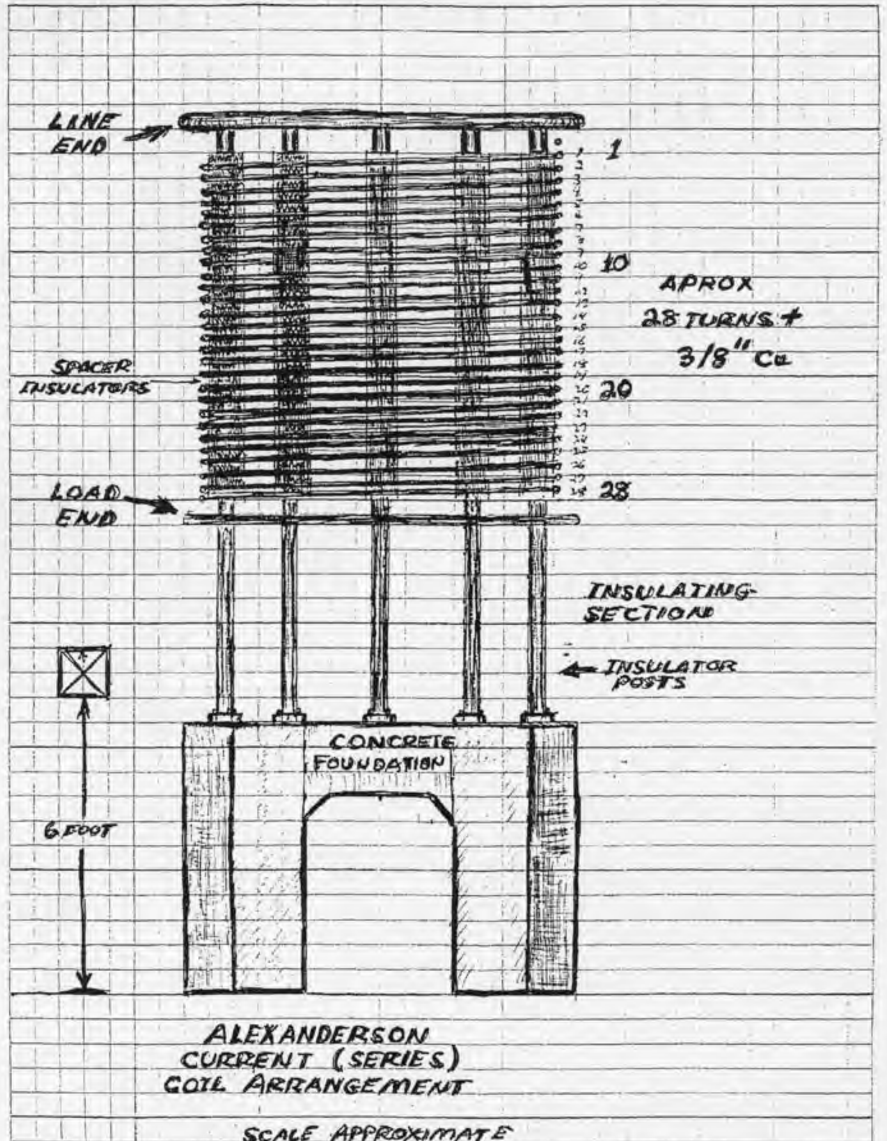


Alexanderson Network



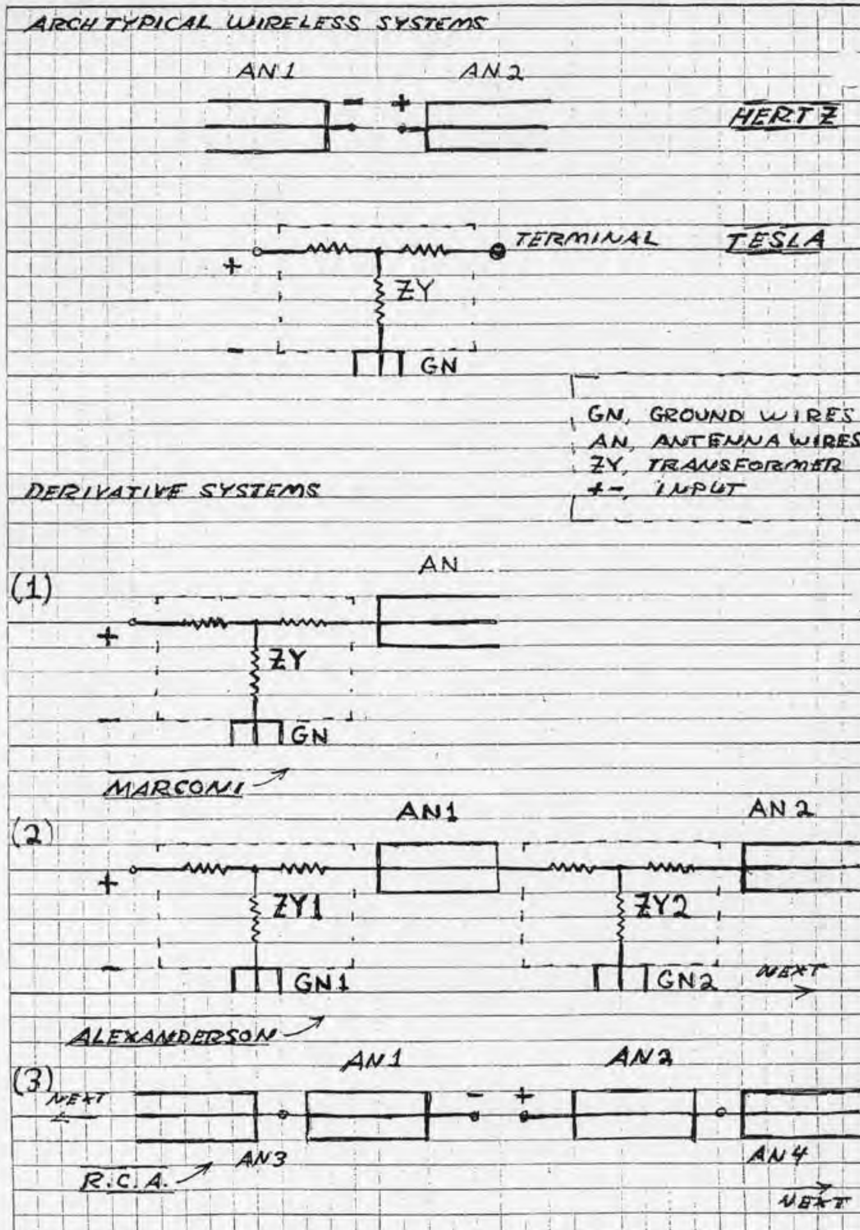
9-5 Alexanderson Potential (Shunt) Coil Arrangement

Shunt Diagram



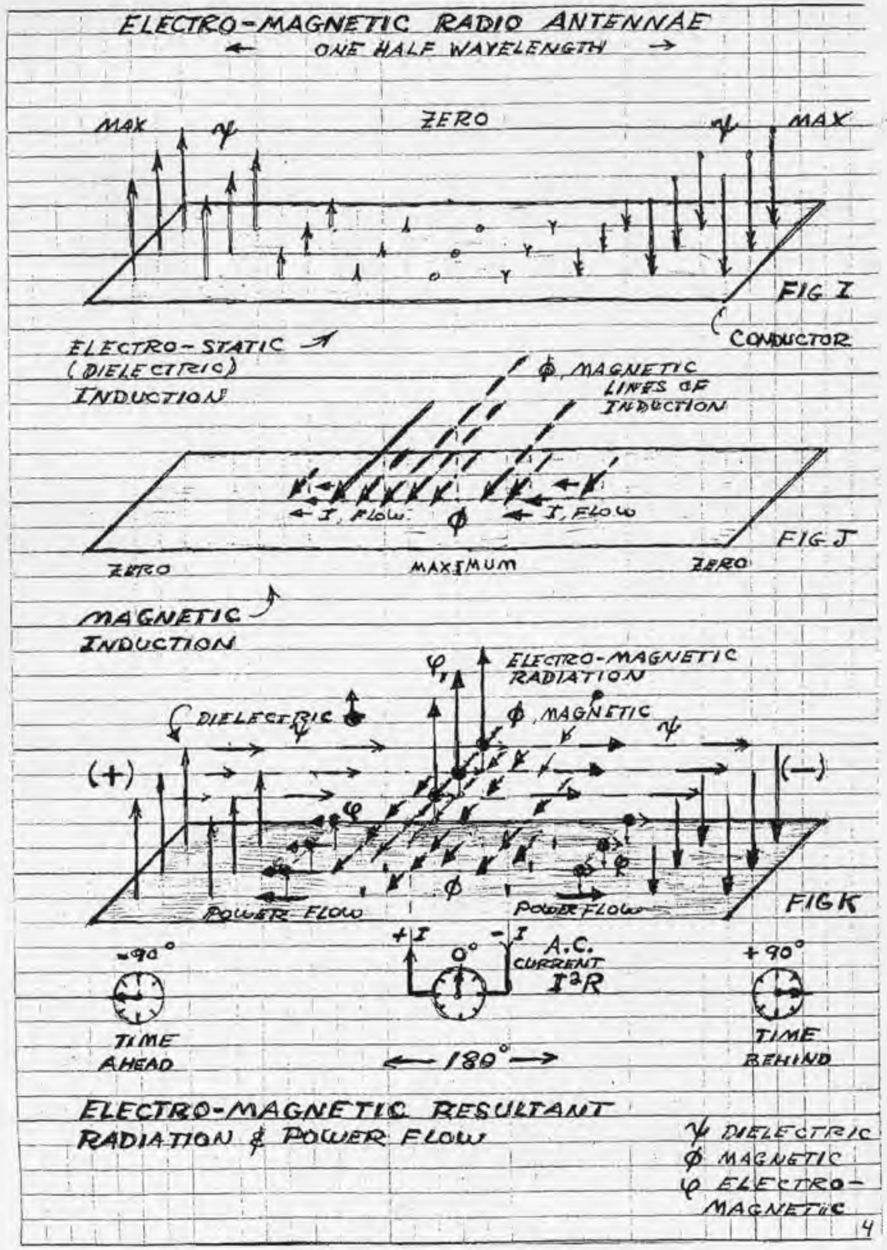
9-6 Alexanderson Current (Series) Coil Arrangement

Coil Arrangement



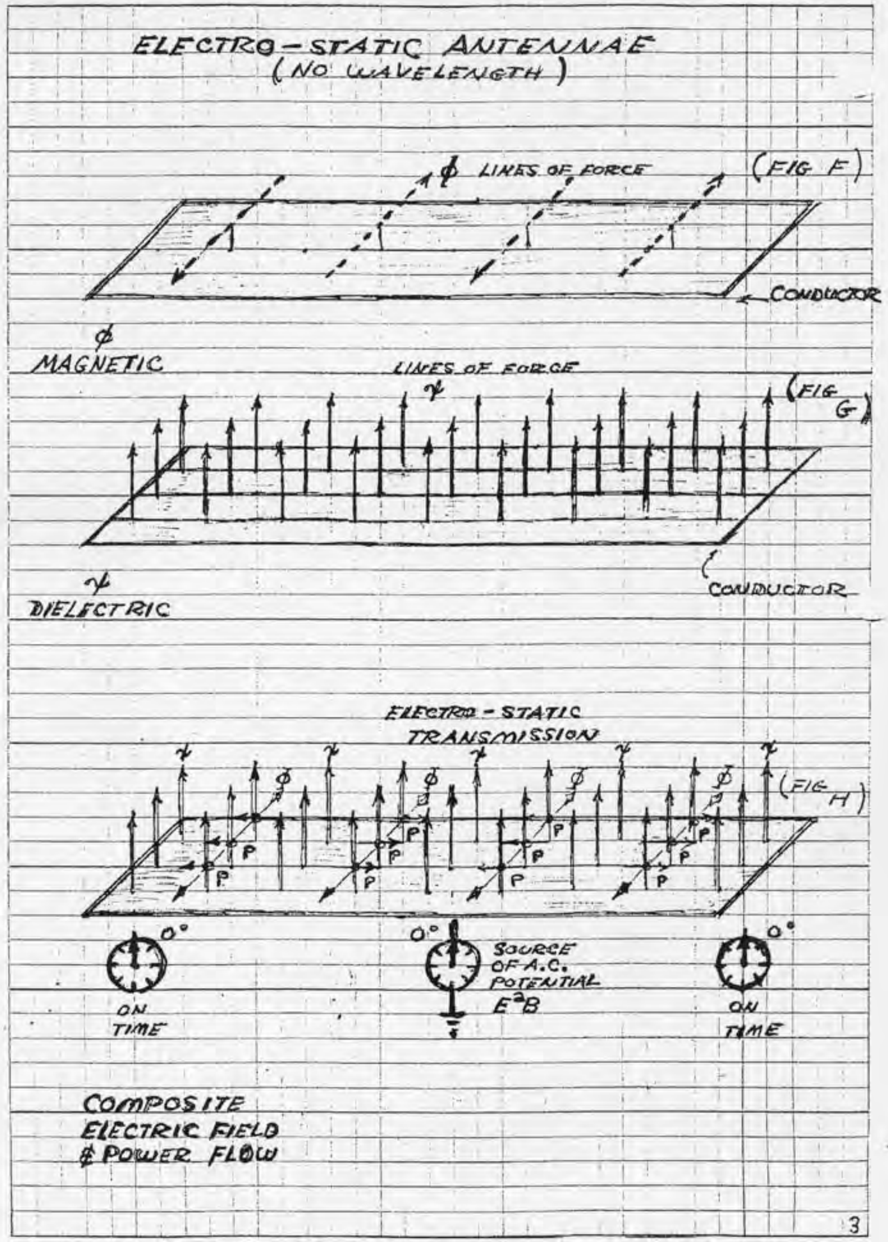
9-7 Archtypical Wireless Systems (2 diagrams) and Derivative Systems (3 diagrams)

Archetypical Systems



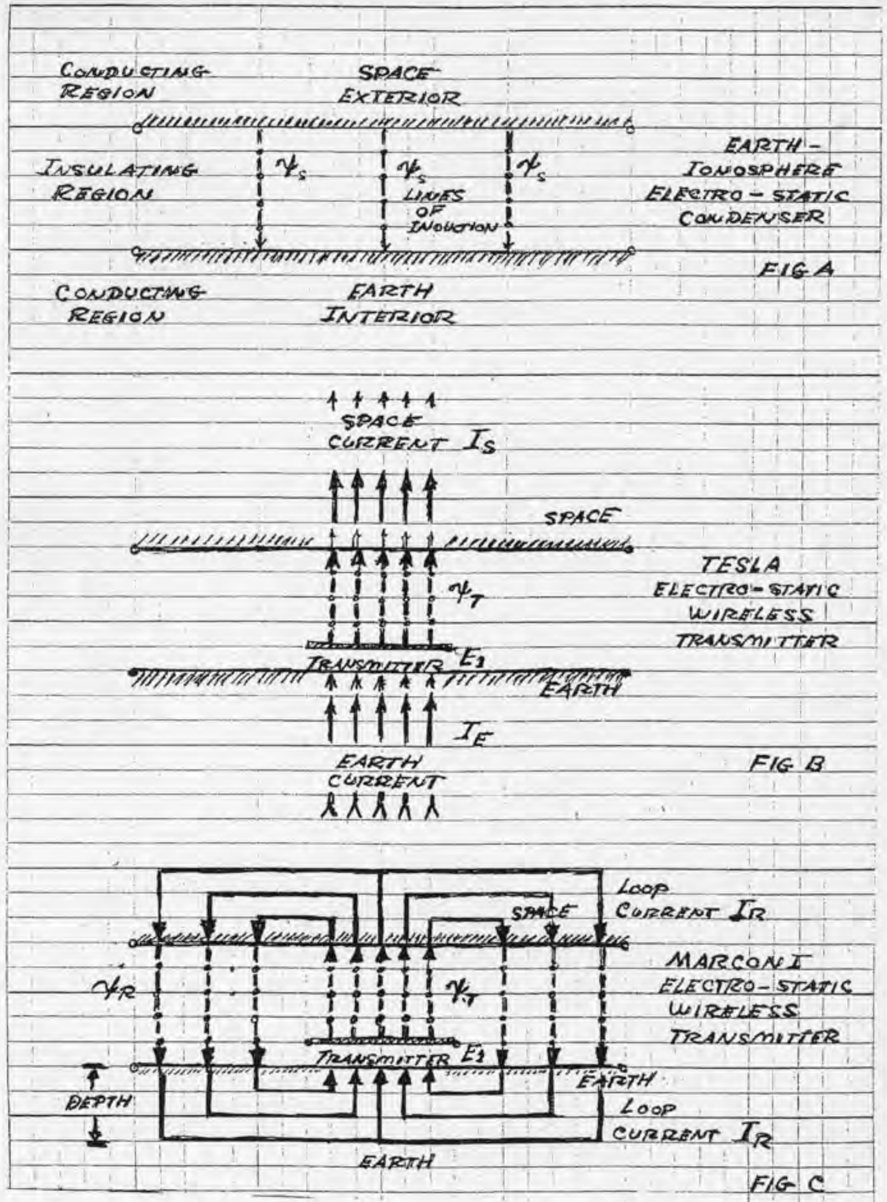
9-11 Electro-Magnetic Resultant Radiation and Power Flow

Power Flow



9-10 Composite Electric Field and Power Flow

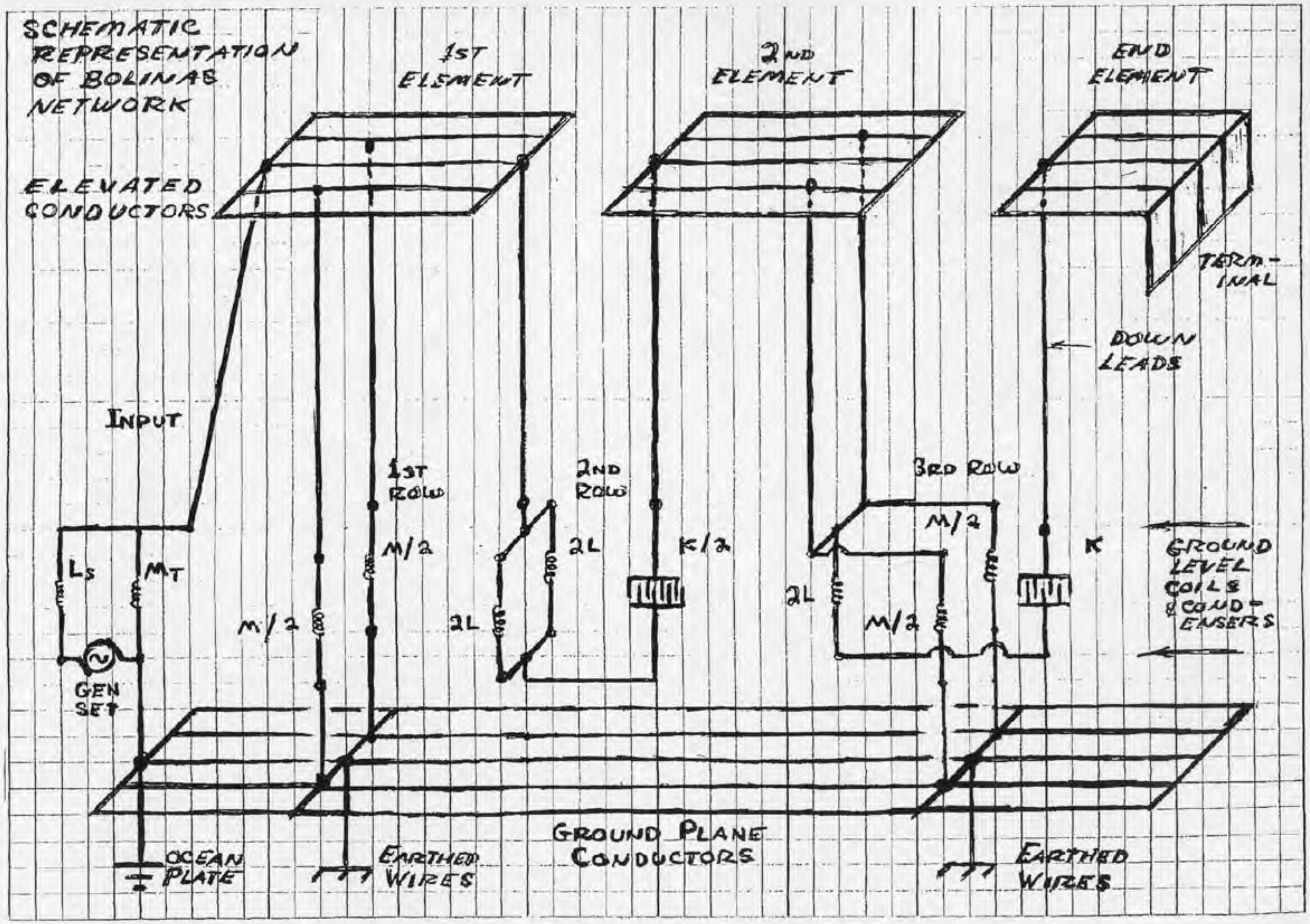
Electro-Static Antenna



9-8 Three diagrams: "Earth-Ionosphere Electro-Static Condenser." (Fig. A); "Tesla Electro-Static Wireless Transmitter." (Fig. B); & "Marconi Electro-Static Wireless Transmitter" (Fig. C).

Electro-Static Condenser

9-12 Schematic Representation of Bolinas Network



Bolinas Schematic

XIII FIRST EXPERIMENTAL SCALE MODEL OF ALEXANDERSON ANTENNA NETWORK

a) SCALE $a = 0.01$, POWER

$a^{1/2} = 0.10$, E.M.F. & CURRENT

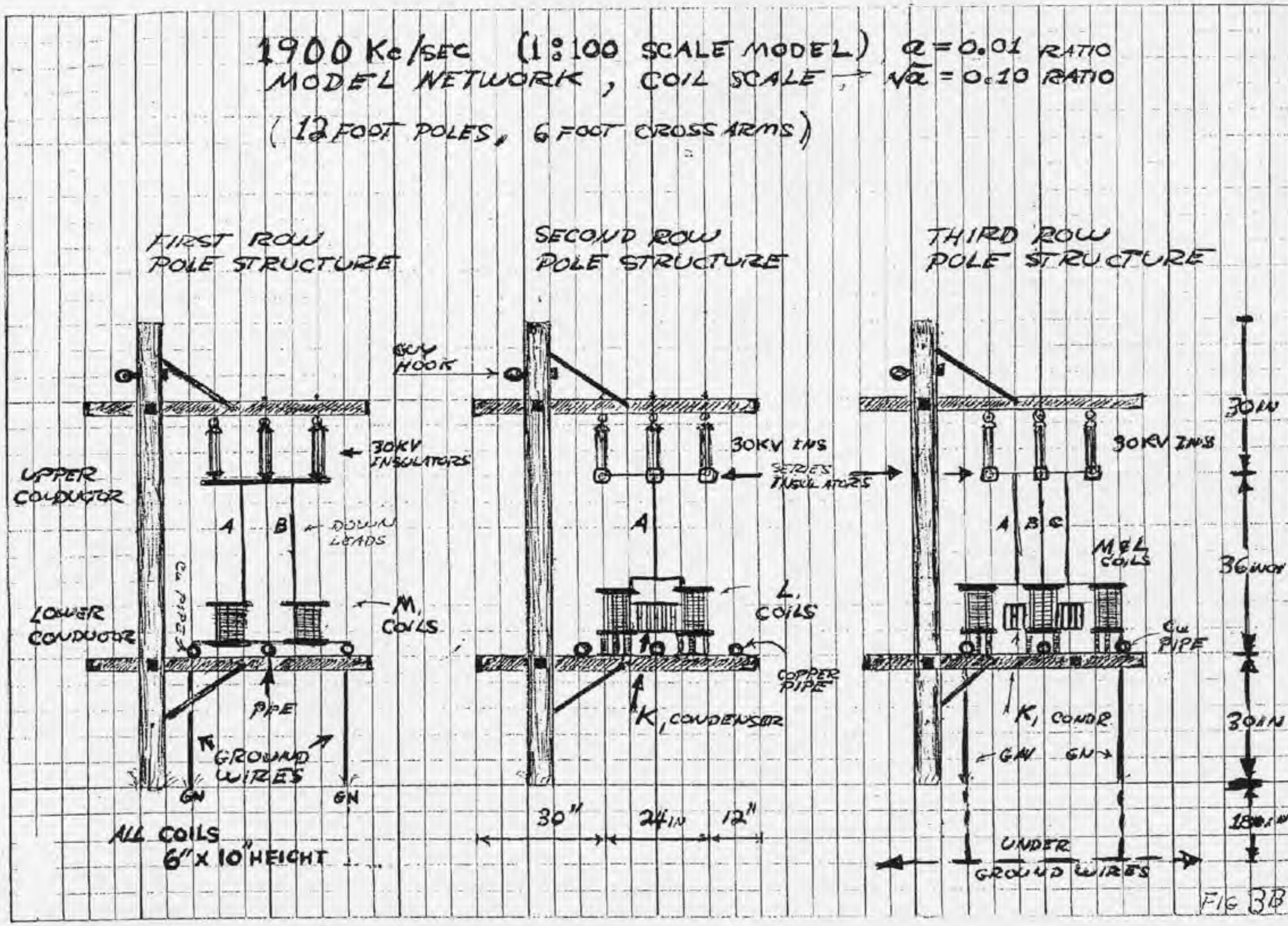
LENGTH	2700 FT a =	27 FT	
EACH ELEMENT	720 FT a =	7.2 FT	l_1 = 86 INCH
WIDTH	240 FT a =	2.4 FT	w = 28 INCH
HEIGHT	300 FT a =	3.0 FT	h = 36 INCH
FREQ	19 Kc/SEC a =	1900 Kc	
COIL HEIGHT	8 FT $a^{1/2}$ =	10 INCH	l_c = 10 INCH
COIL DIAM.	6 FT $a^{1/2}$ =	7 INCH	d = 7 INCH

M =	15 mHy, 1800 Ω	=	150 μHy	, 1800 Ω
$½M$ =	30 mHy, 3600 Ω	=	300 μHy	, 3600 Ω
L_s =	20 mHy, 2400 Ω	=	200 μHy	, 2400 Ω
L =	4 mHy, 480 Ω	=	40 μHy	, 480 Ω
K =	0.018 μFd, 480 Ω	=	180 pFd	, 480 Ω
ω =	1.2×10^5 RAD/SEC		1.2×10^7 RAD/SEC	

9-13 First Experimental Scale Model of Alexanderson Antenna Network

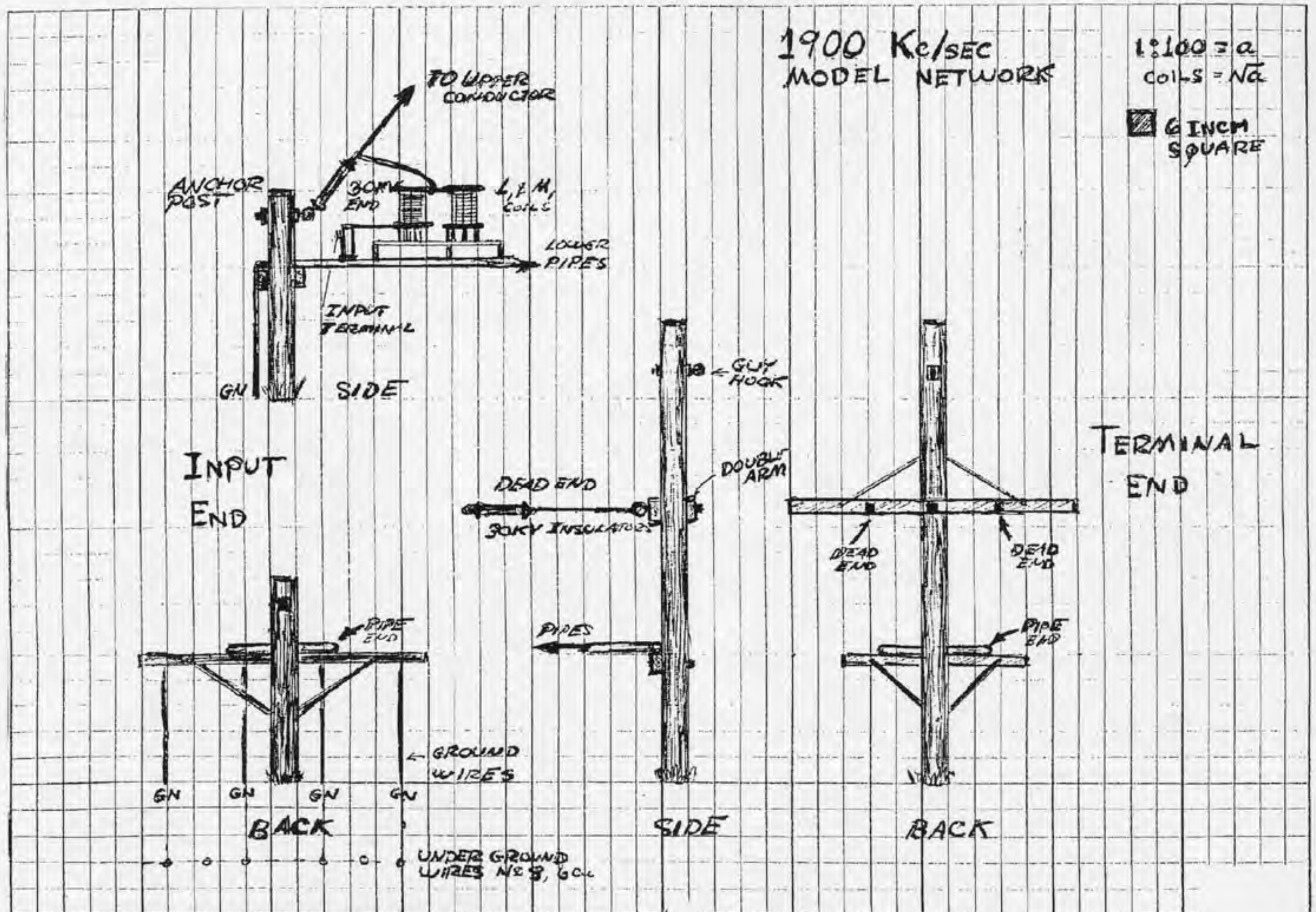
Dimensions

9-14 1900 kc/sec (1:100 scale model) Model Network



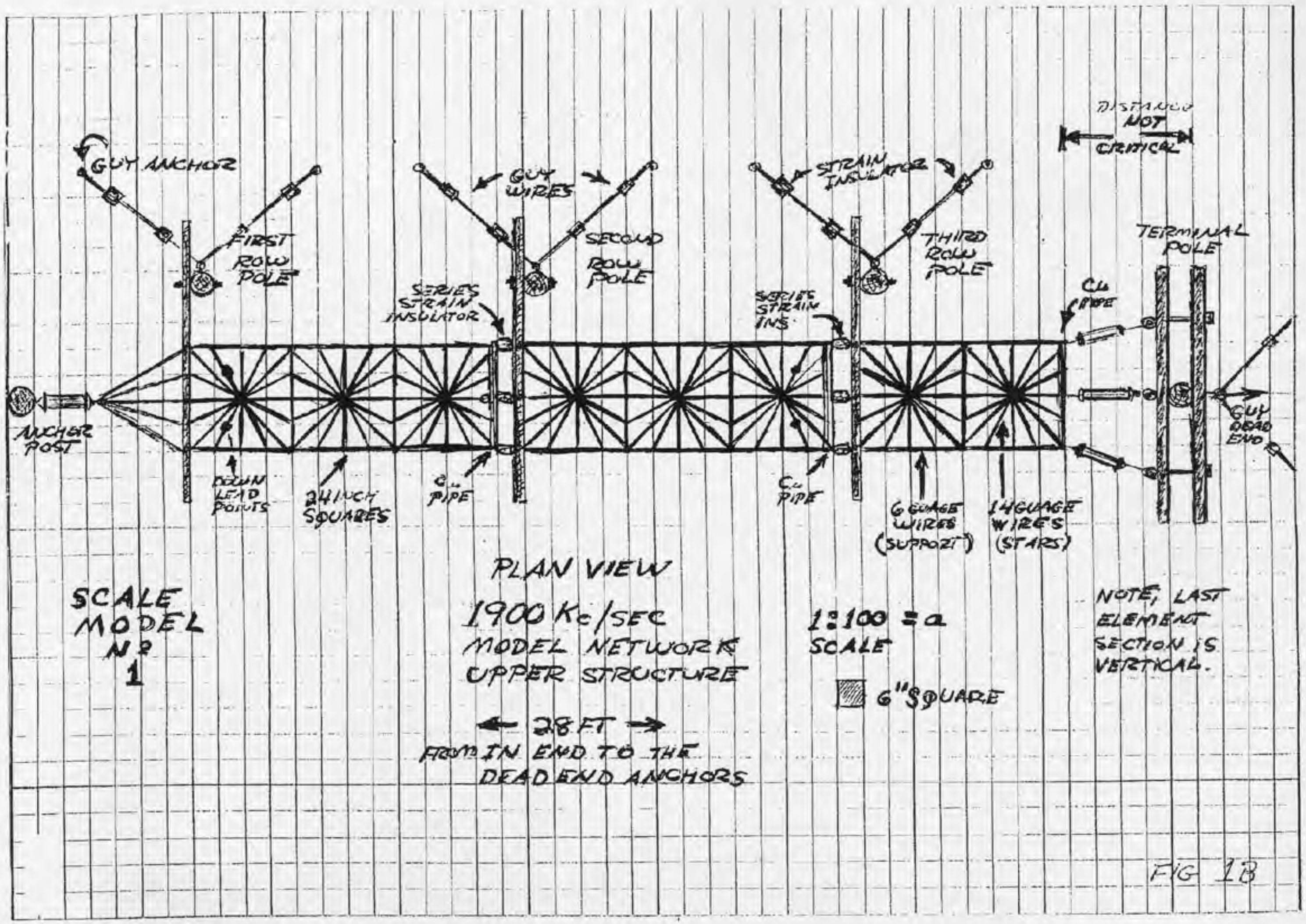
Model Network 1

9-15 1900 Kc/sec Model Network, Input End and Terminal Ends



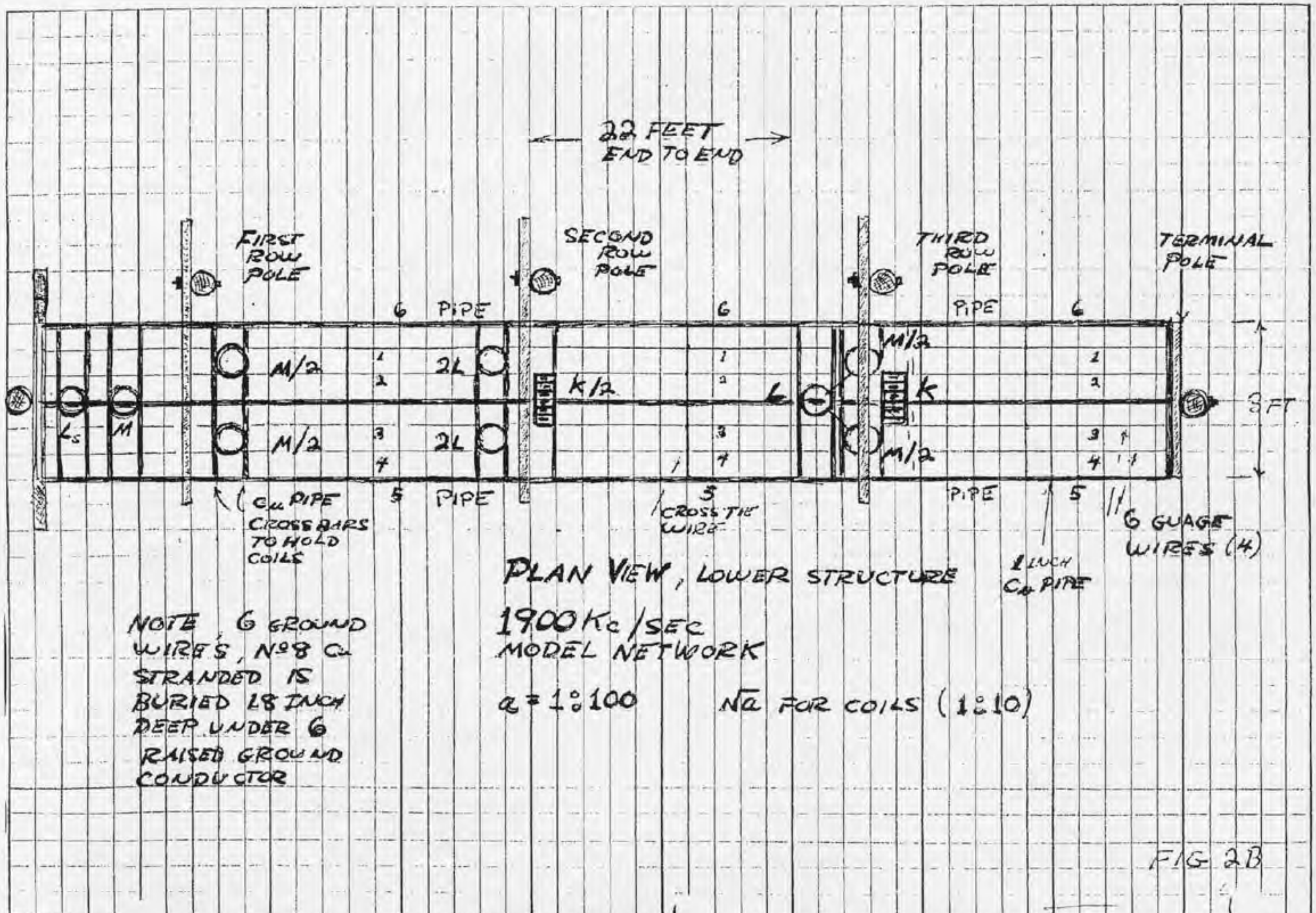
Model Network 2

9-16 1900 Kc/Sec Model Nework, Upper Structure (plan view)



Model Network 3

9-17 1900 Kc/sec Model Network, Lower Structure (plan view)



Model Network 4