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KAJORNSAK HOTRABHAVANANDA for the MASTER OF SCIENCE
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Title: TRANSMISSION LINE TOWER LOCATION BY DIGITAL COMPUTER METHODS USING A PARABOLIC APPROXIMATION

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John F. Engle

In this thesis, a digital computer method for locating transmission line towers is presented. The computer program selects the position of both angle and tangent type towers for a given ground profile. This selection will provide a minimum cost per foot of transmission line in terms of the average costs associated with the basic tower types only.

Basically, this computer program consists of a mathematical simulation of the established manual 'Template Method' for representing the conductor sag characteristics with respect to a ground profile of the existing terrain features. The constraints imposed by the allowable conductor swing and tower side forces are investigated for violation as each span is determined by the computer. The foregoing

features plus the ability to determine them rapidly with alternative tower selections are the major advantages of this computer program.

The program consists of the following distinct algorithms to perform the general functions discussed below:

1) Locate the conductor position in such a manner that a specified minimum ground clearance is not violated in any span length.
2) Locate a tower at the best location on the given ground profile to support the above chosen conductor span.
3) Classify the tower type by examining the uplift condition, the conductor swing angle, the horizontal and vertical tower loads, and the position of angle towers.
4) Calculate the tower cost per unit distance covered for each span.

The choice of towers and their location is determined by an iterative procedure that examines successively each tower type. An overlapping procedure is also used to avoid a span length that would be too short.

The program was tested with a section of ground profile containing an obstruction and a void area. The results have been plotted and shown in this thesis.

Transmission Line Tower Location by Digital Computer Methods Using a Parabolic Approximation

by

Kajornsak Hotrabhavananda

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Professor of Electrical and Electronics Engineering
in charge of major

Redacted for privacy

Head of Department of Electrical and Electronics Engineering

Redacted for privacy

Dean of Graduate School

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Typed by Clover Redfern for Kajornsak Hotrabhavananda

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LIST OF SYMBOLS

AK	parabolic curve constant of hot conductor, numeric.
BK	parabolic curve constant of cold conductor, no ice, numeric.
CK	parabolic curve constant of cold conductor with ice, numeric.
CA	$(TBY + TH_1 - GC)$ a constant calculated by the computer for proper position of the curve above the datum line, feet.
CB	$(TBY + TH_1 - TH_2)$ used the same as CA, feet.
d	parabolic curve constant, AK, BK, or CK will be used instead by the computer, numeric.
D	diameter of conductor, inches.
DIF	difference between tower base curve and ground profile, feet.
GC	minimum ground clearance, feet.
H	axis of symmetry of conductor curve, feet.
HB	axis of symmetry of cold conductor curve, no ice, feet.
HC	axis of symmetry of cold conductor curve with ice, feet.
HMIN	minimum value of H, feet.
ℓ	span length, feet.
P	wind pressure, lbs/ft^2.
r	radial thickness of ice, inches.
S	conductor, feet.
SLX	tower span length, feet.
TBX	tower base station number, feet.

T	tension in conductor, lbs
T_t	tension in conductor at temperature t° F, lbs.
TH_1	first tower height, feet.
TH_2	second tower height, feet.
W	total conductor weight, lbs.
w	weight of conductor per linear foot, lbs/ft.
x_i	station number at point i, feet.
y_i	elevation at point i, feet.
β	line angle, degrees.
θ	swing angle, degrees.

TRANSMISSION LINE TOWER LOCATION BY DIGITAL COMPUTER METHODS USING A PARABOLIC APPROXIMATION

I. INTRODUCTION

The electronic digital computer has developed rapidly into an indispensable aid to modern engineering practice. An area of application which has recently attracted more and more attention is the solution of different kinds of optimizing problems. The high speed capability of the computer allows a large number of alternative combinations to be investigated, compared and evaluated in the same time interval that one solution could be obtained manually. The location of transmission line towers is an example of this type of use.

In the years prior to 1962, most of the transmission line layouts were developed by hand. A considerable amount of time was required to find an acceptable set of tower locations. Due to this time limitation man generally could not determine the most economical set of locations and tower sizes.

A digital computer program was written to utilize the ground profile and tower design data for the fast development of a more economical transmission line layout than could be produced by the manual method. In 1964, Somkiet Phaloprakarn presented a thesis on this subject (11). The procedure employed in that thesis was to fit a catenary curve to the computer-preselected tower locations. The locations of towers were estimated on the basis of tower heights, the design tension for nonflat terrain, and the specified minimum ground clearance. The sag and tension of a conductor were computed directly from the catenary curve. Ground clearance was checked at every survey station including the lowest point of the conductor. Both the tower height and the span length were adjusted by the program until the best combination was obtained.

In this thesis, the procedure used came from a simulation of the manual method. The obstructions and void areas on the ground profile, the tower classification, and the most economical combinations of all tower heights throughout the ground profile are also taken into account. The representation of the ground profile will be read directly into the computer instead of being drawn on a paper. The obstructions and void areas are indicated in the ground profile data. A conductor hanging between two supports is represented by a parabolic curve that is used to simulate the conductor-sag template. The mathematical method used by this program will have the same result as moving a template on the profile drawing. The best position of the conductor is that position at which the clearance between the conductor curve and the ground co-ordinate points (profile) will be equal to the minimum ground clearance for at least one point. At the other points, clearances might be equal to, or greater than, the minimum ground clearance. Then the computer will select the best location of a tower that can support the conductor in that position. The method used in checking the conductor swing angle is the same as the manual method. The horizontal and vertical forces on the conductor will be computed. Then the side swing angle is equal to the arctangent of the ratio of horizontal to vertical force components.

An alternative design, when done by hand, is made by re-plotting the tower heights and locations on the ground profile. This procedure has been integrated into the layout process as the computer program equivalently moves along the profile, in contrast to the manual method. The total cost per foot of transmission line will be calculated and compared for each alternate design. Only the lowest cost design combination will be retained.

The computer program was written in Fortran IV Language for use on the CDC 3300 digital computer at Oregon State University.

II. DIGITAL COMPUTER METHOD

Development of the Ground Profile

The computer program input information consists of the co-ordinates of the right of way and two discrete values of profile elevation data for survey stations. The first ground profile data is the base elevation profile on which towers may be located. The second profile data must be the survey station ground elevation plus the change in the minimum ground clearance that must be maintained at that station. It is permissible to enter the profile co-ordinates at any interval desired. In very rough terrain the enter of the profile co-ordinates should be short.

In any region that requires increased clearance such as side slope areas, telegraph line crossings, railway crossings, or major roads, the second profile elevation data will be used to form the actual ground clearance profile in order to satisfy those conditions. In the opposite case the regions where a tower can not be located are indicated in the first elevation profile data by creating an artificial hole below the datum line. The datum line will be arbitrarily chosen as the reference for the elevation of ground profile. The computer will not locate towers at or between these negative co-ordinates of the base (first) elevation profile. A typical ground profile is shown in Figure 1.

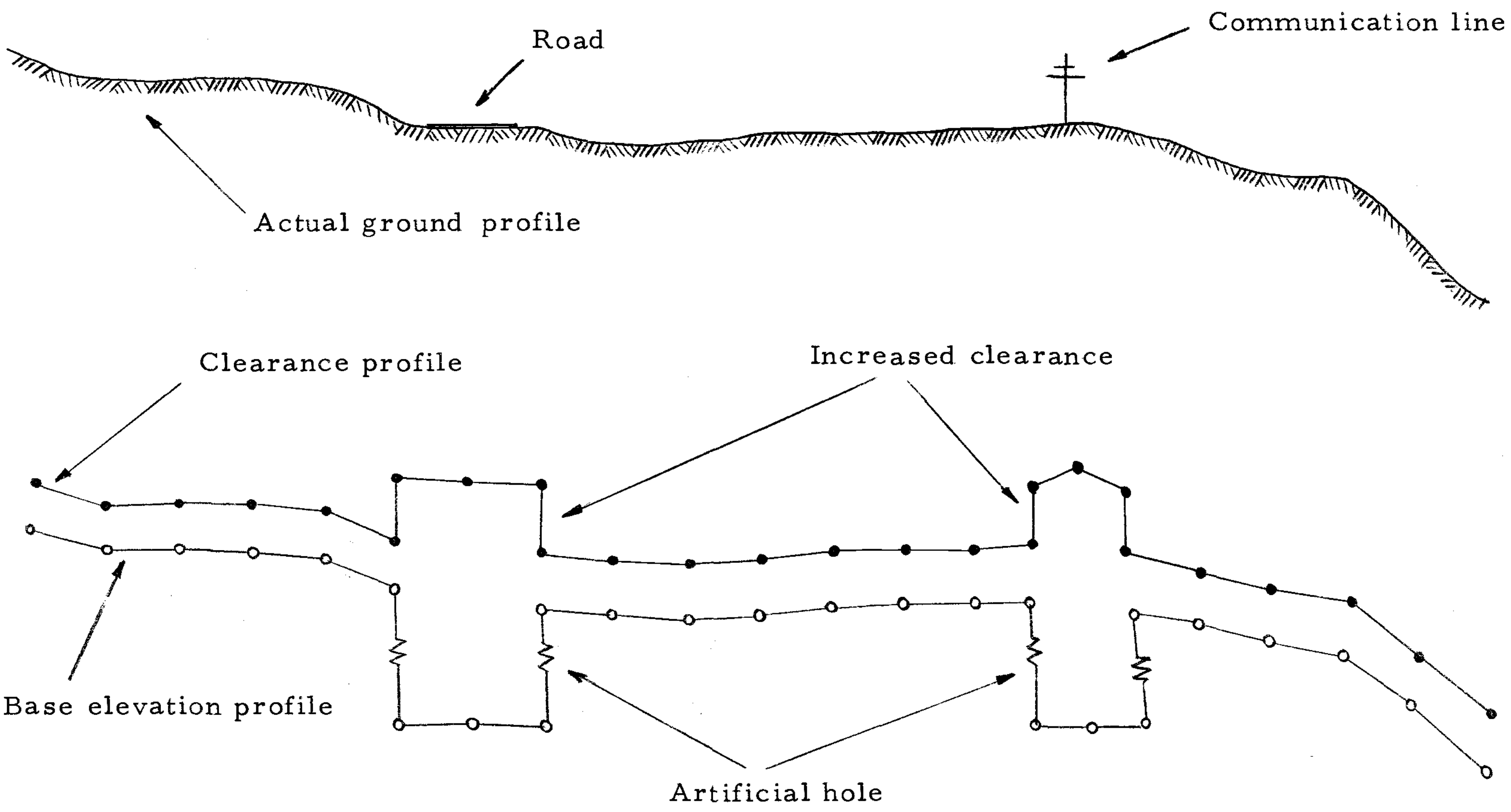

Figure 1. Typical ground profile.

Conductor Sag

A conductor hanging between two supports can be approximately represented by a parabolic curve. The fact that the insulators hang plumb at the time the conductor is erected assures that the horizontal tension is equal in all spans of every length, both level and inclined. Because of this and the parabolic representation, the ratio of the sag to the square of the span length must be a constant as indicated in Equation (1). Therefore the parabolic equation can be extended to any span length by keeping the ratio of the sag to the square of the span length constant.

Mathematical Representation

The sag equation can be obtained from a standard transmission line hand book (10) and has been shown as:

$$S = \frac{w(\ell)^2}{8T_t} \qquad (1)$$

where

S = conductor sag (feet)

w = weight of conductor per linear foot (lbs/foot)

ℓ = length of span between two equal supports (feet)

T_t = horizontal tension existing at the temperature t° F (lbs).

For the span between two supports of equal elevations the maximum sag will occur at the mid-point of the span. A cartesian co-ordinate system with the origin at the point of maximum sag can be constructed (see Figure 2).

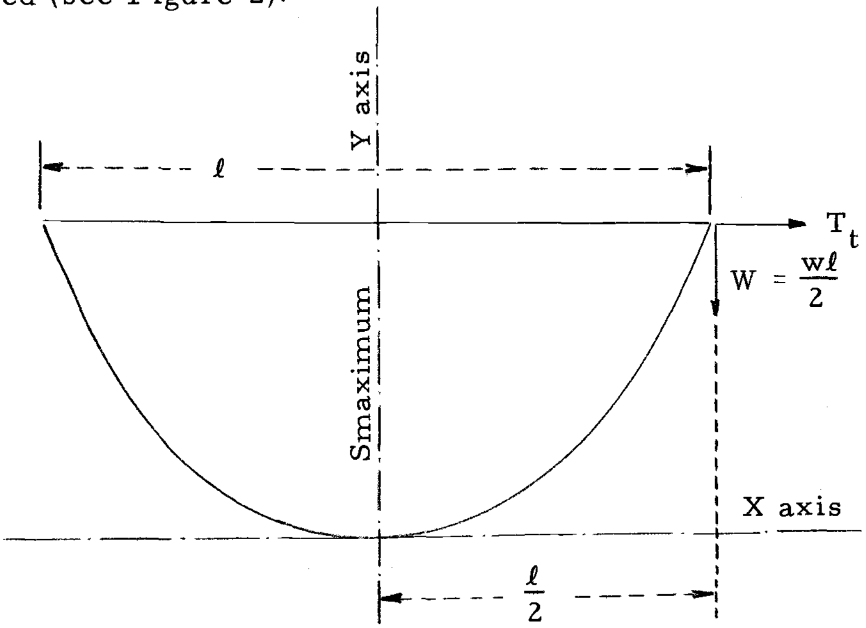

Figure 2. Diagram of a conductor curve.

Then any point on the curve may be represented as:

$$y = dx^2 \tag{2}$$

where d is an appropriate constant.

Representing sag in terms of maximum sag, Smax, as:

$$\text{Sag} = \text{Smax} - y \tag{3}$$

Boundary conditions are such that Sag = 0 only when

$$y = Smax = \frac{w(\ell)^2}{8T_t}$$

and

$$x = \frac{1}{2}(\ell)$$

Then;

$$y = dx^2 = Smax = \frac{w(\ell)^2}{8T_t} = \frac{w(2x)^2}{8T_t} = \frac{w(x)^2}{2T_t}$$

From the above equivalence, a suitable value of d is obtained as:

$$d = \frac{w}{2T_t} \qquad (4)$$

The symbols AK, BK, and CK will be used instead of d by the computer program.

AK is the parabolic curve constant of the conductor sag at the maximum temperature which is used for checking the ground clearance.

Since the tension in the conductor varies under different conditions of temperature or ice load, the position of the conductor will also change relative to the ground profile. The parabolic curve constant at different conditions will not be the same. Therefore the parabolic curve constants of the conductor under different conditions must be known. The symbols for the parabolic curve constants of the conductors other than AK have been shown below.

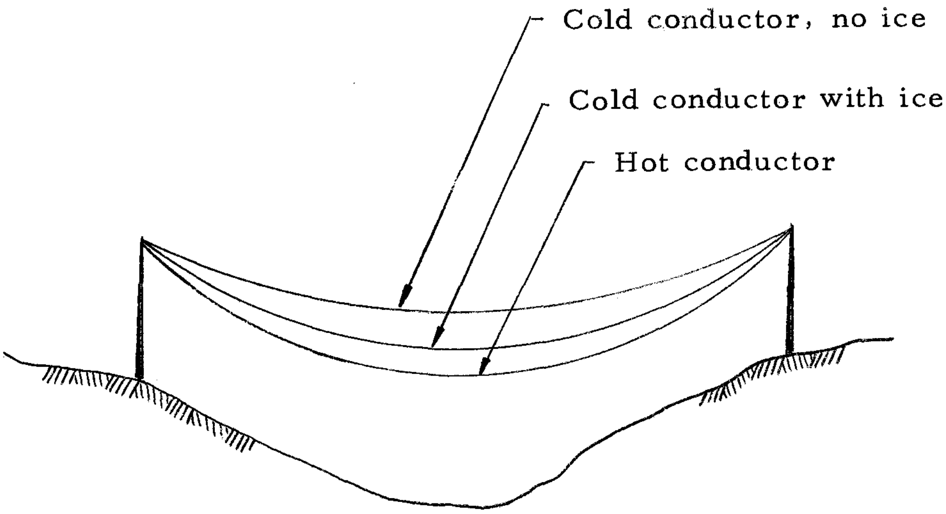

Figure 3. Conductor under different conditions.

BK is the parabolic curve constant of the conductor sag at cold temperature with no ice which is used for checking swing angle.

CK is the parabolic curve constant of the conductor sag at cold temperature with ice which is used for calculation of the tower loading.

Accuracy of the Parabolic Equation in Sag-Tension Calculations

In order to reduce the computing time required, the parabolic curve has been chosen to represent the conductor curve hanging between two equal supports. The parabolic curve has been shown to be accurate enough to be used for sag calculations instead of using the catenary curve by reference (11). The error of the conductor length and sag have been shown in Table 1. For the span length from 100 to 2000 feet the maximum error of the conductor length is

Table 1. Error of the conductor length and sag, conductor size 795 MCM A.C.S.R.

Span Length	Conductor Length Catenary	Conductor Length Parabola	Error in Percent	Conductor Sag Catenary	Conductor Sag Parabola	Error in Percent
100	100.000215	100.000215	0.000000	0.089696	0.089695	0.000008
200	200.001716	200.001716	0.000000	0.358787	0.358785	0.000444
300	300.005793	300.005793	0.000000	0.807274	0.807267	0.000947
400	400.013731	400.013731	0.000000	1.435166	1.435141	0.001716
500	500.026819	500.026818	0.000000	2.242467	2.242408	0.002669
600	600.046343	600.046343	0.000000	3.229192	3.229067	0.003860
700	700.073591	700.073591	0.000000	4.395350	4.395119	0.005261
800	800.109851	800.109847	0.000001	5.740958	5.740564	0.006868
900	900.156411	900.156403	0.000001	7.266032	7.265401	0.008683
1000	1000.214559	1000.214545	0.000001	8.970593	8.969631	0.010726
1100	1100.285581	1100.285559	0.000002	10.854661	10.853253	0.012976
1200	1200.370768	1200.370733	0.000003	12.918263	12.916268	0.015445
1300	1300.471406	1300.471355	0.000004	15.161424	15.158676	0.018127
1400	1400.588785	1400.388711	0.000005	17.584172	17.580476	0.021021
1500	1500.724193	1500.724088	0.000007	20.186540	20.181669	0.024131
1600	1600.878920	1600.878775	0.000009	22.968560	22.962254	0.027454
1700	1701.054254	1701.054058	0.000012	25.930268	25.922232	0.030992
1800	1801.251486	1801.251225	0.000014	29.071704	29.061603	0.034745
1900	1901.471904	1901.471562	0.000018	32.392906	32.580366	0.038710
2000	2001.716800	2001.716358	0.000022	35.893917	35.878522	0.042890

0.000022%, and of the conductor sag is 0.042890% too small.

The equations of the catenary curve and parabolic curve used in calculation of Table 1 have been shown below.

Conductor length (catenary curve) $= \frac{2T}{w} \sinh \frac{w\ell}{2T}$

Conductor length (parabolic curve) $= \ell[1 + \frac{1}{24} (\frac{w\ell}{T})^2]$

Conductor sag (catenary curve) $= \frac{T}{w} (\cosh \frac{w\ell}{2T} - 1)$

Conductor sag (parabolic curve) $= \frac{1}{8}(\frac{w\ell^2}{T})$

Tower Classification

There are at least three basic tower types required for line construction; tangent, small angle suspension, and dead-end structures. The variation in the design, height, and safety requirements of each type represent one of the economic considerations in computerized transmission line design. For each tower height, the information on types, design loadings, and costs will be stored in the computer as a three dimensional array (see Tables 2, 3, 4, and 5). The computer will choose the least expensive tower that satisfies the tower type and loading required to support the conductor at that location. A discussion of each of the basic tower types is given below.

1. A tangent suspension tower is one that can be used for normal span support where no angle in the line occurs.
2. A small angle suspension tower is one that can be used for normal spans with a small turn angle in the line or for a longer than ordinary tangent span support.
3. A dead-end tower is one that can be used for normal span support when a large angle is turned in the line or for extra long tangent spans, or as a full dead-end tower where the line is essentially terminated. In all cases, this tower will be used with anchor cables and the suspension insulators will be in a near horizontal or strain position.

The following factors will be considered in the selection of tower types and strength classes from the table of available towers.

Vertical Load

Vertical load is the load caused by the weight of the conductor plus ice. It can be obtained by the equation:

$$\text{Vertical load} = (\text{Vertical span length}) \times (\text{Unit conductor weight} + \text{Unit ice load}) \tag{5}$$

Where the vertical span of any tower is the sum of the horizontal distances on the left and the right of the tower to the lowest points of the conductors. The nature of a vertical span is shown in Figure 4.

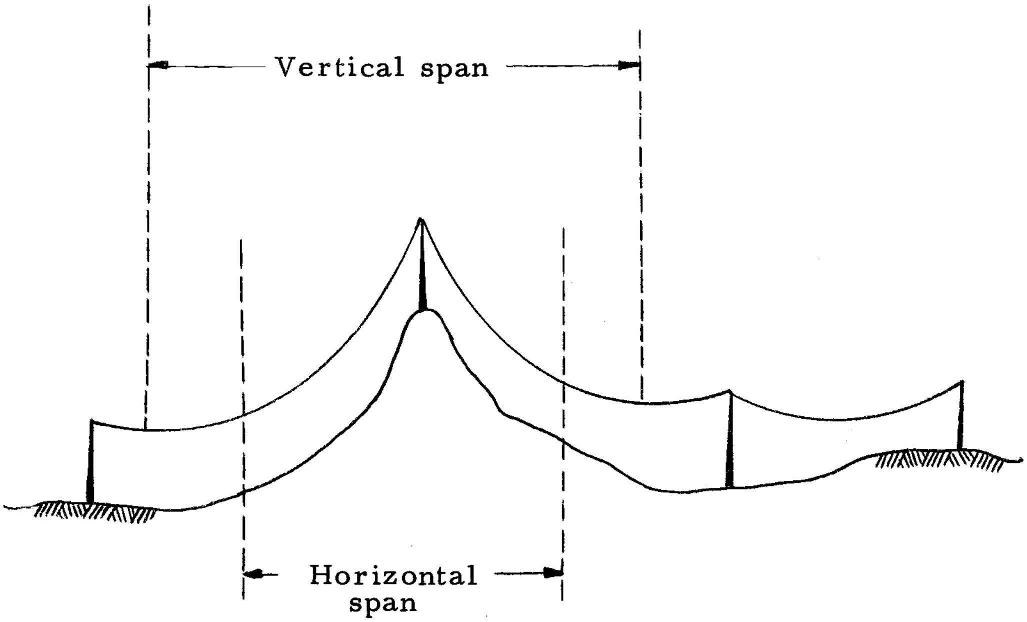

Figure 4. Vertical span and horizontal span.

Unit ice loading is obtained from reference (7) as:

$$\text{Ice load (lbs/ft)} = 0.311[(D+2r)^2 - D^2] \quad (6)$$

in which

D = diameter of conductor in inches

r = radial thickness of ice in inches.

<u>Horizontal Load</u>

Horizontal load is caused in part by wind pressure on the conductor. If the tower is located at an angle point, the transverse component of the line tension must be added to the wind loading.

The horizontal load due to wind pressure is obtained by the equation:

$$\text{Horizontal load due to wind} = (\text{Horizontal span length}) \times (\text{Unit wind load}) \quad (7)$$

where the horizontal span of any tower is half of the sum of the two tower span lengths on the left and the right of that tower (see Figure 4).

Unit wind loading for conductors is obtained from reference (7) as:

$$\text{Wind load (lb/ft)} = \frac{P}{12} D \quad (8)$$

in which

P = wind pressure in pound per square foot

D = diameter of conductor in inches.

The transverse component of the line tension is obtained by the following equation:

$$\text{Horizontal load due to tension} = 2T(\sin \frac{\beta}{2}) \quad (9)$$

where

T = tension in the conductor in pounds

β = angle in the profile line in degrees

The total horizontal load on an angle tower will be the algebraic sum of these loads in Equations (8) and (9) as in Figure 5.

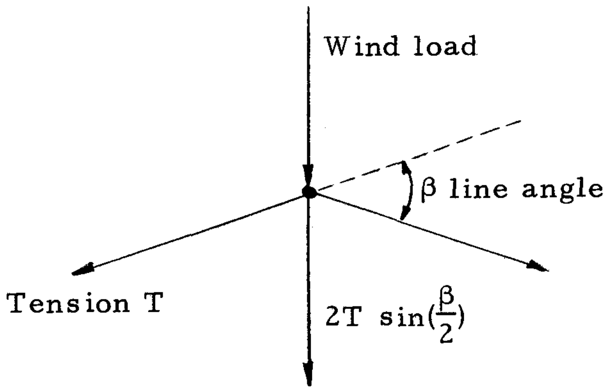

Figure 5. Vector diagram of horizontal loads.

Uplift on Insulator

Every span from tower to tower is part of a large imaginary span (see Figure 6). If there is an intermediate tower of such height as to just touch the imaginary span, the outside towers will carry the entire load, leaving the intermediate tower unloaded (see Figure 7).

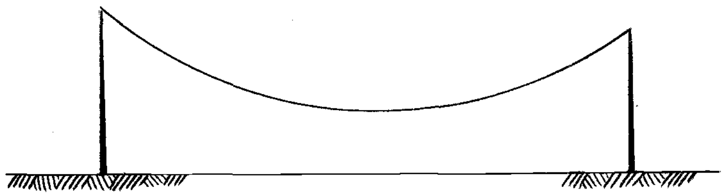

Figure 6. Two towers support the imaginary span.

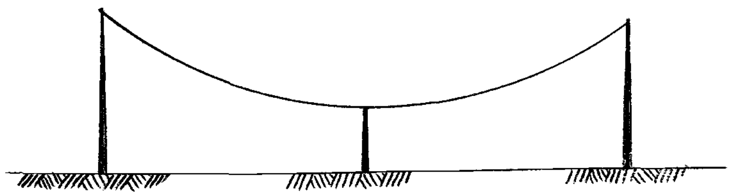

Figure 7. The intermediate tower unloaded.

If the intermediate tower is of such height as to lift the wire above the imaginary span, the intermediate tower will carry part of the load (see Figure 8). If, on the other hand, the intermediate tower pulls the wire below the imaginary span, there will be an uplift on the intermediate tower, tending to detach the wire from its insulator (see Figure 9).

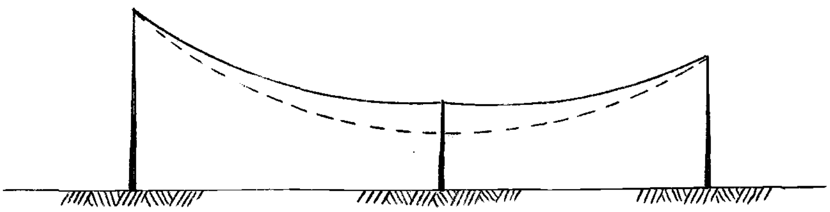

Figure 8. The intermediate tower carries part of the load.

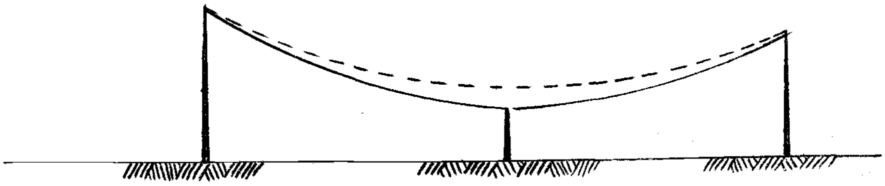

Figure 9. An uplift at the intermediate tower.

The uplift condition would result in a negative vertical load, and will be determined at the same time the side swing angle is determined.

Side Swing Angle

The angle that the insulator is deflected sidewise from the vertical must be investigated in order to determine the minimum clearance to the steel-work. The angle of insulator swing can be found from the equation:

$$\theta = \tan^{-1}\left(\frac{\text{Wind pressure on conductor and insulator}}{\text{Weight load of conductor and insulator}}\right) \qquad (10)$$

Usually the weight of the insulator and the wind pressure on it are negligible when compared to the weight and wind pressure on the conductor.

Then;

$$\theta = \tan^{-1}\left(\frac{\text{Wind load}}{\text{Weight load}}\right) \qquad (11)$$

For suspension angle towers, the horizontal load due to tensions $(2T \text{ sine } \frac{\beta}{2})$ must be added to the wind load.

The maximum side swing angle will occur when the direction of the wind is in the same direction as the horizontal angle load (see Figure 5). The side swing angle may be negative if the direction of wind is opposite to angle load.

If the side swing angle is greater than the allowable limit, the next higher tower will be used. If it can not be reduced to less than the allowable limit after using the tallest tower available, the dead-end tower will be used.

Transmission Line Tower Location

The steps used in developing the computer method for locating transmission line towers are described below.

Conductor Position

The first tower must have been specified and located by the input information. The computer will then find the position of the conductor in such a manner that the conductor passes through the point of attachment on the first tower while proper ground clearance is maintained throughout the span forward from the first tower. The conductor curve in this position will have the clearance curve that is tangent to one or more ground profile points with the difference between the curve and all other ground profile points being positive. The clearance curve is the curve that has the same characteristic but the elevation is lower than the conductor curve by a distance equal to the minimum ground clearance (see Figure 10).

A succession of parabolic ground clearance curves that pass through a common point on the equivalent tower and each ground profile point will be generated (see Figure 11). This curve generation starts with the first survey station forward from the tower. Each curve will yield a different axis of symmetry, H (the distance from the tower to the lowest point of the curve). The nature of the axis of

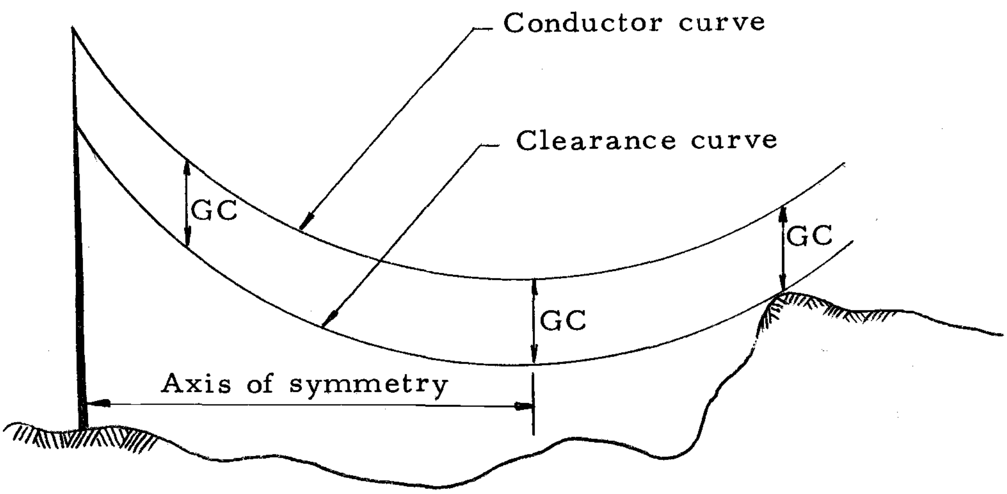

Figure 10. Conductor and clearance curves.

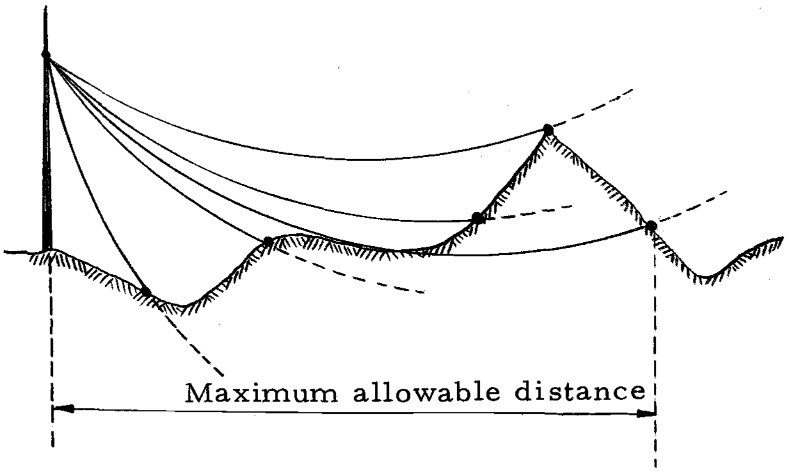

Figure 11. Parabolas through a common point on the tower and a number of ground profile points.

symmetry is shown in Figure 10. As this succession continues by using the next forward ground profile point, the computer will compare each value of H to the previous least value and the lesser of the two will be retained. The process will stop when the curve passes through the last ground profile point in that interval. Therefore the last value of H retained is the minimum value. The clearance curve that is tangent to one or more ground profile points with the difference between the curve and all other ground profile points being positive will have the minimum value of H. This has been proved in Appendix II.

The axis of symmetry of a curve that is tangent to the ground profile at any point can be obtained by the equation:

$$H = \frac{d(x_i - TBX)^2 + CA - y_i}{2d(x_i - TBX)} \qquad (12)$$

The derivation of this expression appears in Appendix I. The minimum value of H will be denoted as HMIN in the computer program.

Tower Position

Having determined the proper position of the conductor curve, the next step in the program is to locate the position of the second tower. Because of uneven terrain, there may be several places in the interval where a tower of a given height may be placed (see Figure 12). These are the intersections of the tower base curve and the ground profile. The tower base curve is the curve that has the same characteristic as the conductor curve but the elevation is lower equal to the tower height of the second tower (TH_2). The equation of tower base curve using the value of HMIN previously determined can now be formed. The equation is shown as:

$$Y_i = AK[(x_i\text{-}TBX)^2\text{-}2\,HMIN(x_i\text{-}TBX)] + CB \qquad (13)$$

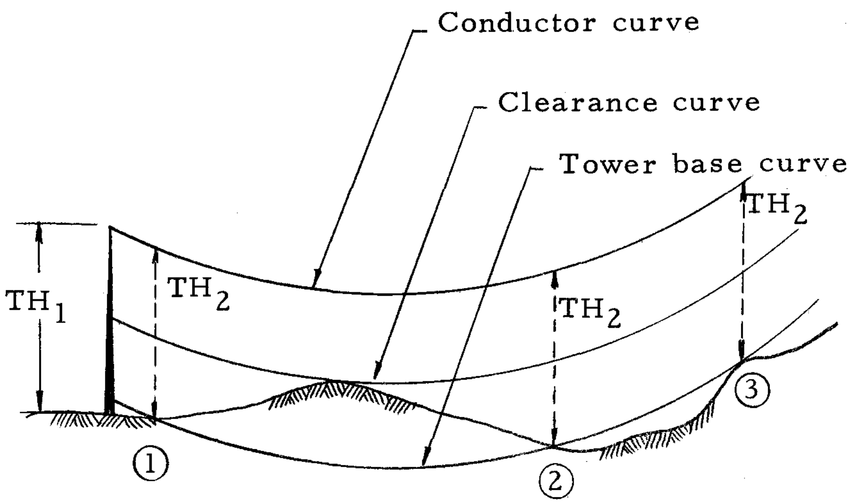

Figure 12. Three possible locations of the second tower.

Since a simultaneous solution is not possible, the following difference between the tower base curve and ground profile will be formed as:

$$DIF = y_i - Y_i \qquad (14)$$

DIF may have three different values (-), (0), and (+). If DIF is equal to zero at any survey station, the tower can be exactly located at that station number. If there is any change in sign of DIF from (+) to (-), or from (-) to (+) between any survey stations, it means that there is an intersection of the tower base curve and ground profile. Further calculations are required in order to find the location of the second tower. By assuming that both tower base curve and ground profile between these two station numbers are straight lines, the two straight line equations can be formed. The intersection of the two straight lines is at the co-ordinate point (x, y), which is the position of the second tower (see Figure 13).

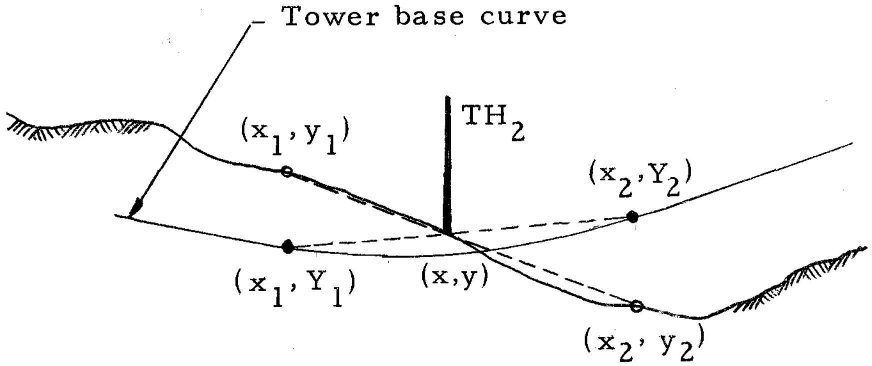

Figure 13. Intersection of two straight lines.

The two straight line equations are formed and the unknown x and y can be easily solved as:

$$x = x_1 + \frac{(x_2 - x_1)(y - Y_1)}{(Y_2 - Y_1)} \tag{15}$$

$$y = \frac{Y_1 y_2 - Y_2 y_1}{Y_1 - Y_2 + y_2 - y_1} \tag{16}$$

The computer will determine the possibility of the second tower positions, starting from the far end of the allowable span backward to the first tower. Then the position selected is the one that can provide the greatest span length.

Cold Conductor Position

The classification of each tower is related to the horizontal and vertical conductor loads that are functions of the horizontal and vertical spans. In order to calculate these, the axis of symmetry must also be known at the cold temperature. The axis of symmetry of the cold conductor curve can be obtained from the equation:

$$HB = \frac{BK(SLX)^2 + CA - TBY_2}{2(BK)(SLX)} \tag{17}$$

In case of cold conductor with ice, the axis of symmetry can be obtained from the equation:

$$HC = \frac{CK(SLX)^2 + CA - TBY_2}{2(CK)(SLX)} \tag{18}$$

III. DIGITAL COMPUTER PROGRAMMING

Program Description

The program was written in Fortran IV for use on the CDC 3300 computer at Oregon State University. It has been divided into a main program and several special subroutines. For convenient reference and to clarify the subsequent analysis, the main program and subroutines are briefly described below:

Main program: This is an executive type program to provide control of the input, output, and logical flow of the computations. The necessary data for initialization and operation of the subroutines are read in by the main program. Then the subroutines are subsequently called and executed under the direction of this program. The main program also controls the logical flow of the combinations of all possible tower heights and types as specified for the relocation-tower precedure.

Subroutine, Sub 1: This subroutine will find the position of the conductor curve. The shape of the conductor curve is approximated by a parabola. The location of the conductor curve giving minimum clearance is found by fitting parabolas through the conductor attachment point on the tower and successive profile co-ordinate points. The clearances between the conductor curve and ground co-ordinate points will at least be equal at one point to the minimum ground clearance. At the other points, clearances might be equal or greater than the minimum ground clearance. The conductor in this position is represented by the parabola for which the distance between the tower and the lowest point on the curve is minimum (which is the value of HMIN).

Subroutine, Sub 2: After projecting a minimum clearance conductor curve from a tower by means of subroutine, Sub 1, the next tower is located by finding the point where a tower of given height fits exactly between the conductor curve and the ground profile. This is done by subroutine, Sub 2, which works backward from a point located a specified distance forward of the base tower until such location is found. The computer will not locate the tower at the point where the base elevation profile is below the datum line.

Subroutine, Sub 3: If there is a specific point in the profile where a tower must be located, the subroutine, Sub 3, will be called to locate a given tower at that point. In case a given tower is too high to support the minimum clearance conductor curve projected by the subroutine, Sub 1, the computer will increase the value of the minimum ground clearance in order to raise the elevation of the conductor curve so that a given tower can fit exactly between the conductor curve and the ground profile. Any given tower that is too short to reach the conductor curve projected by the subroutine, Sub 1, at that point will not be used.

Subroutine, Sub 4: After the second tower has been located, the subroutine, Sub 4, will be called to find the axis of symmetry of the cold conductor curve both with and without ice. These values will be used in calculation of the swing angle and tower loading.

Subroutine, Sub 5: This subroutine is used to calculate the horizontal load and the vertical load of the tower and also to calculate the value of swing angle of the insulator.

Subroutine, Sub 6: The cost of the tower will be selected by the subroutine, Sub 6, from a three-dimension cost array (height, type, and strength class) entered with the line data. The least expensive tower that meets the requirements will be used.

Computer Operation

After the profile lines and other data are read in, the subroutine, Sub 1, will be called to find the conductor position. The subroutine, Sub 2, is called next in order to find the location of the second tower. If there is a horizontal angle in the ground profile, the subroutine, Sub 3, will be called to position a tower at that angle point. As each tower is positioned, the previously positioned tower is checked for loading by the main program. If it is a suspension tower, the combined subroutines, Sub 4 and Sub 5, will be called to check the maximum swing angle. Then the subroutine, Sub 6, is called to select the least expensive tower for that tower height. Tower positioning continues until three towers are located. A series of three steps resulting in the placement of three towers is called a pass. The first pass tried by the computer corresponds to using the shortest tower heights. All of the towers in the pass can be fully identified except the last tower in the pass, since its loading is known on only one side. The average basic cost for the last tower will be used to compute the total tower cost for that pass. The tower cost per foot is obtained by dividing total distance by the total cost for the towers and line used during that computing pass.

The search for more economical combinations is accomplished by raising and relocating each tower one at a time. The raising and relocating process starts at the last (third) tower position of the first combination. After all available heights have been tried at the third position, the process moves to the second position and continues. Each height of the second position will give rise to many other possibilities in the third position. The total ground distance covered by each pass will change as the tower heights are changed and new terrain features are encountered. An example of the combinations possible for the pass of three positions and two available tower heights is shown in Figure 14. For each combination, the cost per foot will be compared with the previous least expensive one. The lesser of the two will be retained. The most economic combination (least cost per foot) will be obtained after all possible combinations have been tried.

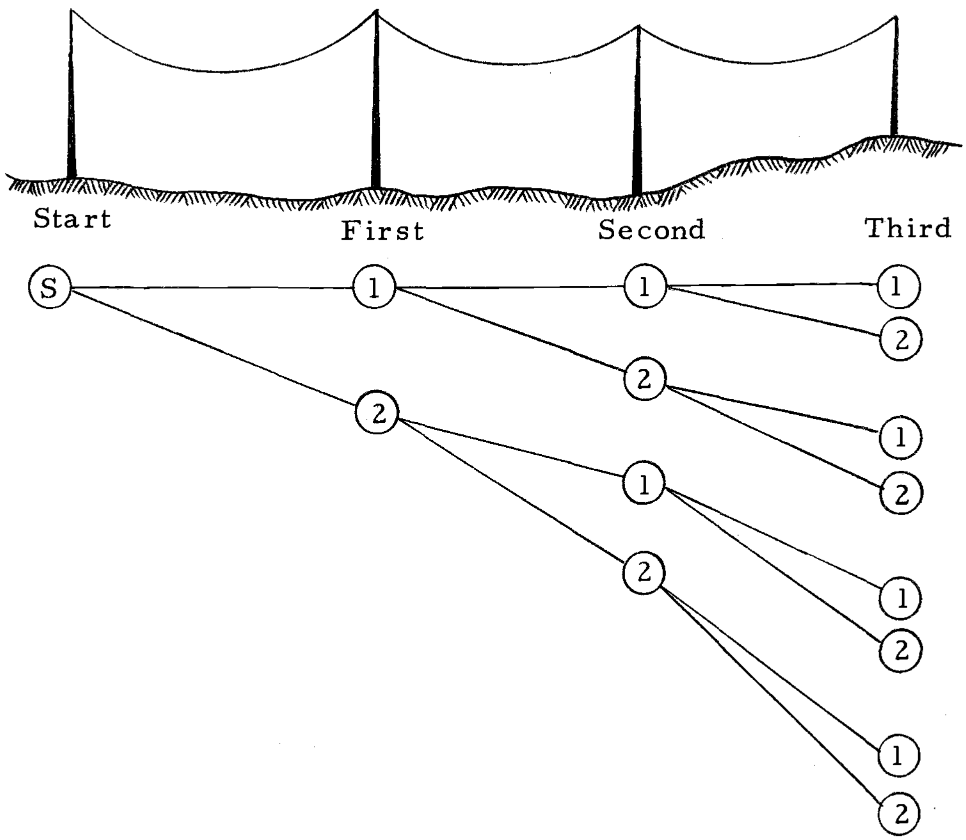

Figure 14. Operation of the computer in combination of towers when two tower heights are available for three positions in the pass.

Foresight Feature

Since the area in the locations of towers may well contain rivers or roads or similar areas where a tower cannot be located, it is possible that the last tower of a given pass may be located 200 or 300 feet short of the edge of such a void area. In some cases, the tower must be located at the edge of the long void area in order to span the entire void area. Then, whenever this condition exists, the first tower must be located on the edge of the void area. This will result in a very short span of 200 or 300 feet from the last tower of the previous pass. This is not an economical location, but the use of a foresight feature will avoid such occurrences.

This feature is accomplished by discarding the last two towers of a pass. Then the remaining tower, which is the first position tower in the pass, will be used as the starting tower of the next pass. The tower location process begins again, 'lapping' over the last few tower positions. The permanent positioning of more than one tower at a time restricts the flexibility of the run, thus increasing the cost per foot of the line design. With the foresight feature, the computer time cost will be higher but the cost of saving of the line design will be more.

Program Testing

Testing of the program was carried out with the sample profile data for the line shown in Figure 15. The ground profile represents nonflat terrain with void areas, a line angle, and a communication line that must be crossed. The other necessary input data for this program are shown below:

Input Data

Parabolic curve constant AK = 0.000171

Parabolic curve constant BK = 0.000156

Parabolic curve constant CK = 0.000171

Tension desired for a hot conductor = 3195 lbs

Tension desired for a cold conductor, no ice = 3500 lbs

Tension desired for a cold conductor plus ice = 6122 lbs

Wind pressure = 4 lbs per square foot

Conductor weight, no ice = 1.092 lbs/foot

Conductor weight plus ice = 2.094 lbs/foot

First tower height = 55 feet

First tower station number = 1200 feet

First tower base elevation = 792 feet

Minimum allowable span = 400 feet

Maximum allowable span = 1500 feet

Design loading and cost of each tower height has been shown in Tables 2, 3, 4, and 5.

Computer Output

The computer will print out information for each tower of the most economical combination determined for the line design. The tower number, tower location, base elevation of the tower, tower height, axis of symmetry of hot and cold conductor curves, tower span, conductor length, horizontal span and load, vertical span and load, line angle, tower type, and cost are printed as the output format. The total cost, total span length, and the cost per foot are printed out at the end of the computation. In order to give the designer the total conductor length used, the conductor length of each span has been accumulated and the total conductor length is printed out at the end of the result. An example of the computer output for the problem tested is shown in Table 6. The results of the tower location for this example have been plotted on the ground profile and shown in Figure 15.

Table 2. Design loading and cost of 45 foot tower height.

Tower type	Class 1			Class 2			
	Vertical load (lbs)	Horizontal load (lbs)	Tower cost (Dollars)	Vertical load (lbs)	Horizontal load (lbs)	Tower cost (Dollars)	Basic cost (Dollars)
Tangent suspension (1)	7200	2200	1900	9600	2900	2200	2000
Angle suspension (2)	8400	3500	2300	1080	4500	2450	2000
Light angle (3)	9650	6900	2800	12100	7450	2950	2500
Heavy angle (4)	7500	11500	9900	9900	15800	3750	2500

Table 3. Design loading and cost of 59 foot tower height.

Tower type	Class 1			Class 2			
	Vertical load (lbs)	Horizontal load (lbs)	Tower cost (Dollars)	Vertical load (lbs)	Horizontal load (lbs)	Tower cost (Dollars)	Basic cost (Dollars)
Tangent suspension (1)	7200	2200	2300	9600	2900	2550	2500
Angle suspension (2)	8400	3500	2850	10800	4500	3000	2500
Light angle (3)	9650	6900	3300	12100	7450	3450	3100
Heavy angle (4)	7500	11500	3950	9900	15800	4200	3100

Table 4. Design loading and cost of 75 foot tower height.

Tower type	Class 1 Vertical load (lbs)	Class 1 Horizontal load (lbs)	Class 1 Tower cost (Dollars)	Class 2 Vertical load (lbs)	Class 2 Horizontal load (lbs)	Class 2 Tower cost (Dollars)	Basic cost (Dollars)
Tangent suspension (1)	7200	2200	2700	9600	2900	3000	3100
Angle suspension (2)	8400	3500	3350	10800	4500	3600	3100
Light angle (3)	9650	6900	3950	12100	7450	4300	3800
Heavy angle (4)	7500	11500	5250	9900	15800	5700	3800

Table 5. Design loading and cost of 90 foot tower height.

Tower type	Class 1 Vertical load (lbs)	Class 1 Horizontal load (lbs)	Class 1 Tower cost (Dollars)	Class 2 Vertical load (lbs)	Class 2 Horizontal load (lbs)	Class 2 Tower cost (Dollars)	Basic cost (Dollars)
Tangent suspension (1)	7200	2200	3200	9600	2900	3550	4200
Angle suspension (2)	8400	3500	4150	10800	4500	4600	4200
Light angle (3)	9650	6900	5000	12100	7450	5200	5000
Heavy angle (4)	7500	11500	5950	9900	15800	6400	5000

Table 6. Transmission line tower locations by digital computer.

TOWER NUMBER	SURVEY STATION	BASE ELEVATION	TOWER HIGHT	AXIS OF SYMMETRY HOT	AXIS OF SYMMETRY COLD	TOWER SPAN BACKWARD	CONDUCTOR LENGTH	HORIZONTAL SPAN	HORIZONTAL LOAD	VERTICAL SPAN	VERTICAL LOAD	LINE ANGLE	TOWER TYPE	TOWER COST
1	1200.00	792.00	59.0	328.96	328.81									
2	1856.37	805.87	45.0	203.04	194.36	656.37	657.75	621.56	1307.15	837.17	5259.09	0	1	1900.00
3	2443.13	810.00	59.0	230.31	215.37	586.76	588.02	679.09	1428.13	769.11	4831.52	0	1	2300.00
4	3214.55	820.00	90.0	510.53	512.24	771.43	774.75	878.44	1847.35	1051.64	6606.43	0	3	5000.00
5	4200.00	845.00	59.0	366.63	361.79	985.45	990.12	909.70	4795.06	933.53	5864.46	9.0	3	3300.00
6	5033.95	859.36	59.0	377.58	371.62	833.95	836.89	856.55	1801.34	989.29	6214.75	0	1	2300.00
7	5913.11	878.00	59.0	285.10	269.25	879.16	882.67	889.54	1870.71	965.63	6066.09	0	1	2300.00
8	6813.04	912.74	75.0	421.70	421.01	899.93	904.90	878.78	1848.07	1100.94	6916.11	0	3	3950.00
9	7670.67	930.83	59.0	451.47	461.39	857.63	860.70	777.19	1634.43	1070.93	6727.60	0	1	2300.00

TOTAL COST 23350.00 DOLLARS
TOTAL DISTANCE 6470.67 FEET
COST PER FOOT 3.61 DOLLARS
TOTAL CONDUCTOR LENGTH 6495.79 FEET

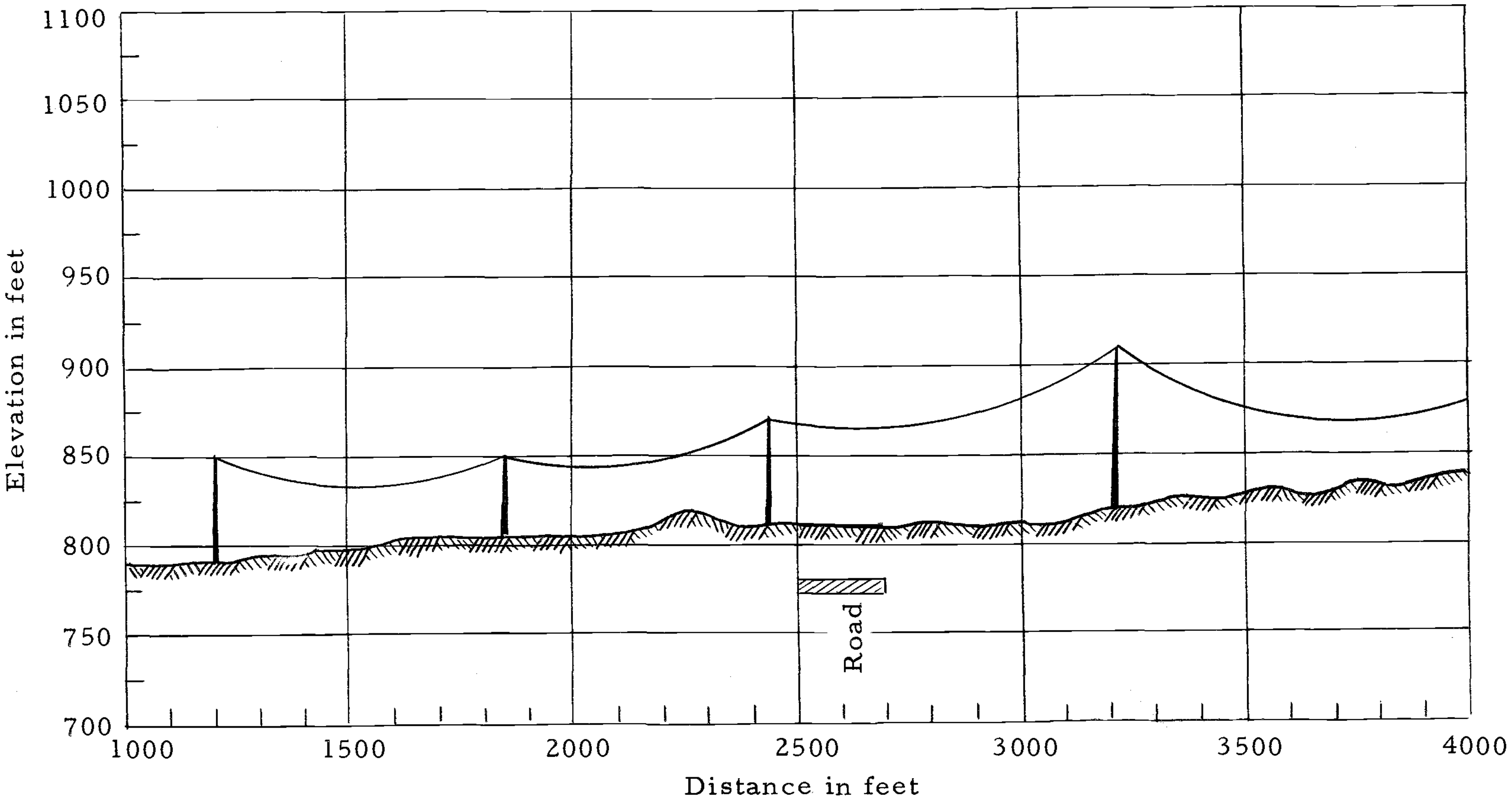

Figure 15. Ground profile and transmission line tower locations.

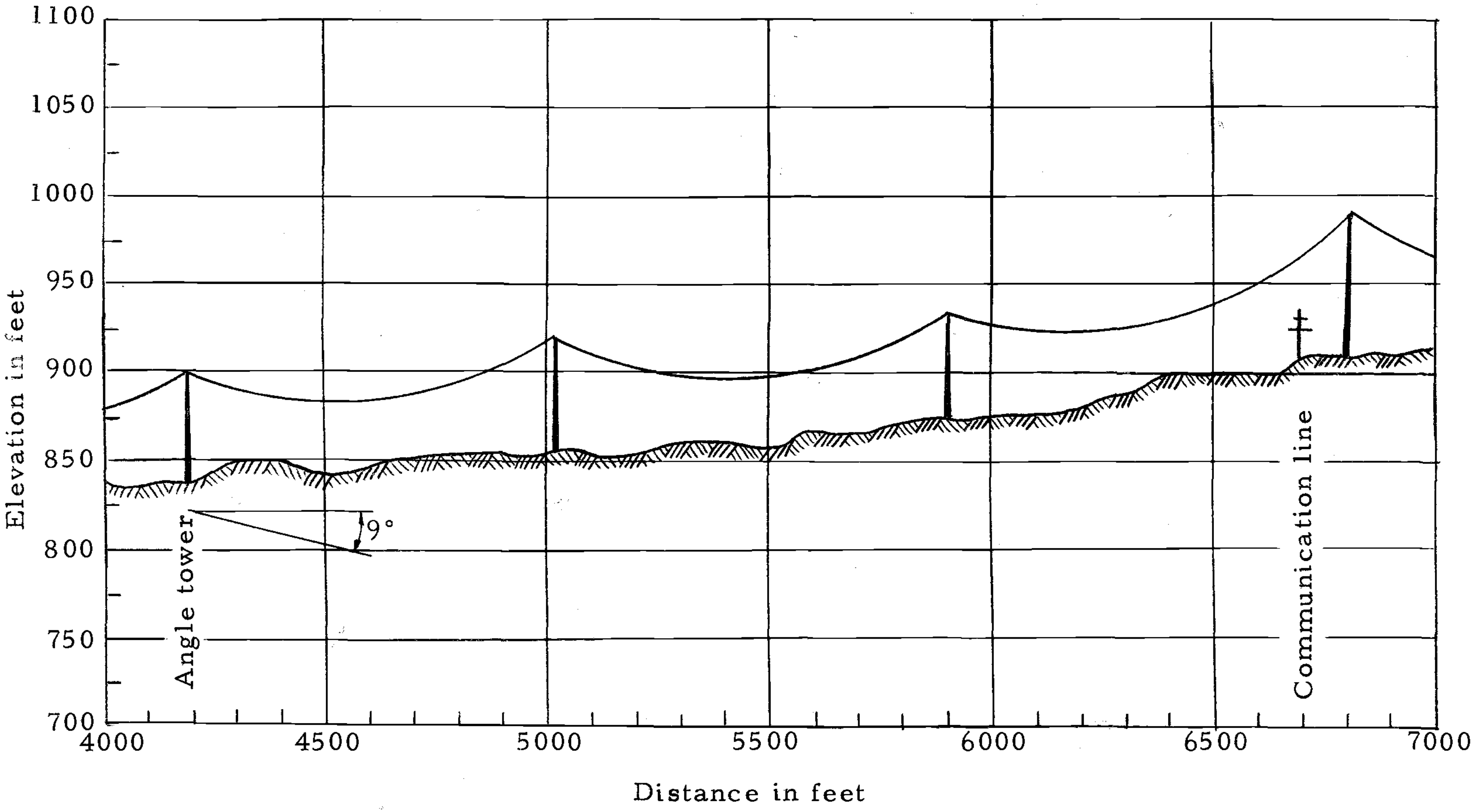

Figure 15. Continued.

IV. CONCLUSION

A digital computer can be used efficiently and economically for transmission line design. The investigation of the computer program has shown that it is possible to use the digital computer to locate transmission line towers over non-flat terrain conditions containing a wide variety of line crossings and areas of restricted structure locations.

The transmission line tower location by digital computer enables the design engineer to investigate several alternate routes for entire or partial line sections in order to obtain data for preparing cost comparisons based upon more reliable cost estimates. It eliminates the use of profile drawing. The field survey notes could be converted directly into computer input and the computer output could be used to order the structural components and to approximately locate the tower foundations in the field.

The computer time required to process a line varies with the length of line, number of discrete points on the ground profile, the number of angle towers, irregularities of the terrain and, most significantly, with the number of tower heights included in the analysis.

An expected saving in the cost of the line construction by this method over the manual method is estimated to be about 10%. These savings are the result of using fewer structures and/or shorter structures over a given distance. The classification of towers will also result in loading a tower more closely to its design limits.

This program is a general one. It can be easily developed for use with different computers and line design specifications.

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APPENDICES

APPENDIX I.

The equation for a parabola through an origin at the vertex is:

$$y = dx^2 \qquad (19)$$

In determining the point of tangency with the ground profile, it is necessary to move the clearance curve either right or left (see Figure 16). At the same time, it must be moved down in order that the curve always passes through the origin to ensure that the conductor will always reach the conductor attachment point of the tower.

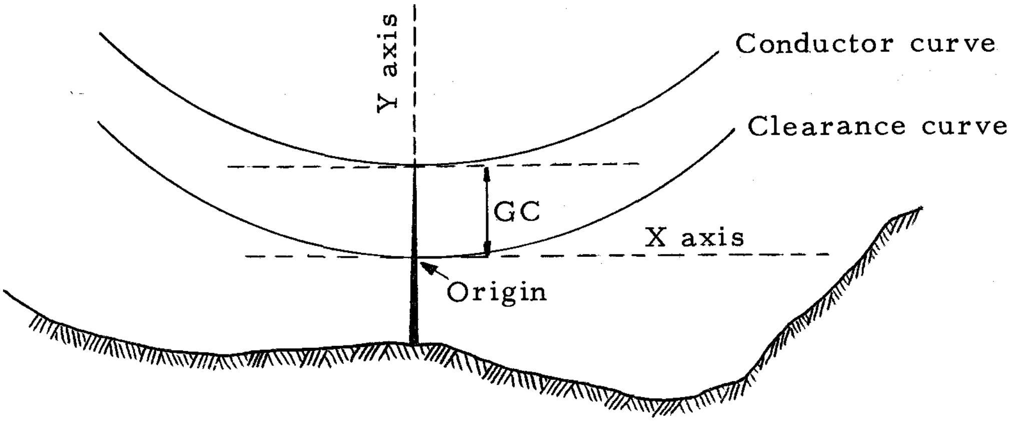


Figure 16. Initial position of clearance curve.

Let the curve be shifted a distance H to the right or left and the curve must be shifted k distance vertically. In order to accomplish this, the vertex of the curve must move along the mirror reflection of the original curve. Then Equation (19) will be:

$$y - k = d(x-H)^2 = d(x^2-2Hx+H^2) \tag{20}$$

For the mirror reflection of the curve, the equation will be:

$$y = -dx^2 \tag{21}$$

Moving the vertex along this curve H units horizontally and k units vertically.

Then;

$$k = -dH^2 \tag{22}$$

Substitute Equation (22) into (20) then,

$$H = \frac{1}{2dx}(dx^2-y) \tag{23}$$

In order to relate this curve to a cartesian co-ordinate system where the X axis is considered as some datum line and the Y axis is zero in the terms of station numbers, the origin is shifted to the left for TBX units distance and down CA units distance as in Figure 17.

Then Equation (23) will be:

$$H = \frac{d(x-TBX)^2+CA-y}{2d(x-TBX)} \tag{24}$$

A series of values of x and y will be substituted into the above equation. The representation of this is Equation (11).

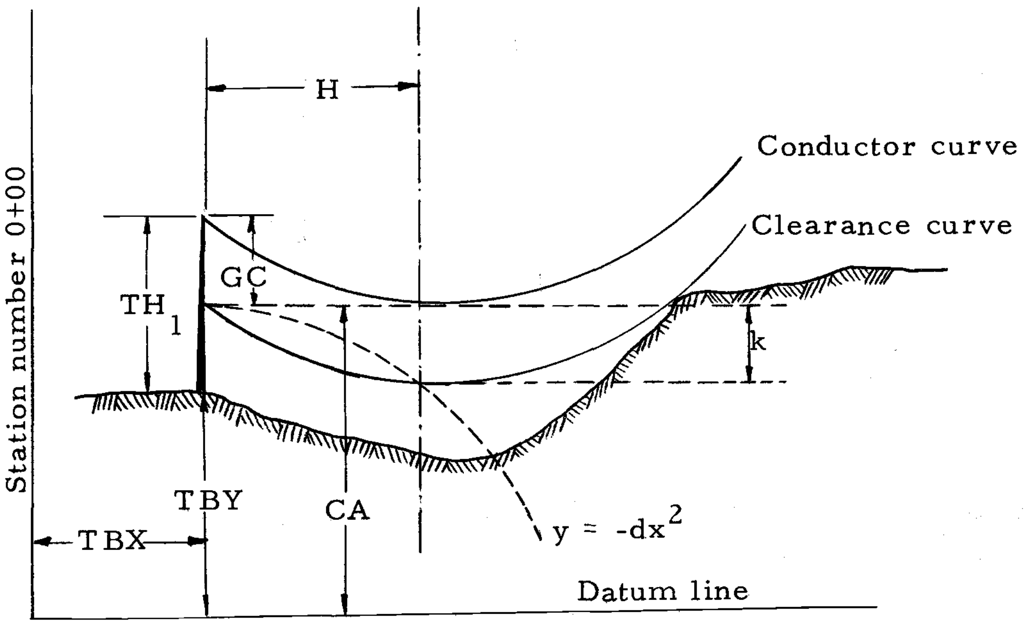


Figure 17. Tangent clearance curve to a ground profile point.

APPENDIX II.

Let curves A, B, and C which have the same parabolic curve constant pass through the common point T on the tower and ground profile points A, B, and C respectively. The values of H_A, H_B, and H_C will be the axis of symmetry of curves A, B, and C as in Figure 18. The relation of the axis of symmetry and the ground profile point of the curves that pass through points A, B, and C can be obtained from Equation (24) as:

$$H_A = \frac{d(x_A - TBX)^2 + CA - y_A}{2d(x_A - TBX)} \tag{25}$$

$$H_B = \frac{d(x_B - TBX)^2 + CA - y_B}{2d(x_B - TBX)} \tag{26}$$

$$H_C = \frac{d(x_C - TBX)^2 + CA - y_C}{2d(x_C - TBX)} \tag{27}$$

The co-ordinate of every point on curves A, B, and C must also satisfy Equations (25), (26), and (27) respectively.

If the points on curves A, B, and C have the same value of the X ordinate equal to x_i then values of the Y ordinate must be equal to y_{ai}, y_{bi}, and y_{ci} respectively (see Figure 18).

Then Equations (25), (26), and (27) will be:

$$H_A = \frac{d(x_i - TBX)^2 + CA - y_{ai}}{2d(x_i - TBX)} \quad (28)$$

$$H_B = \frac{d(x_i - TBX)^2 + CA - y_{bi}}{2d(x_i - TBX)} \quad (29)$$

$$H_C = \frac{d(x_i - TBX)^2 + CA - y_{ci}}{2d(x_i - TBX)} \quad (30)$$

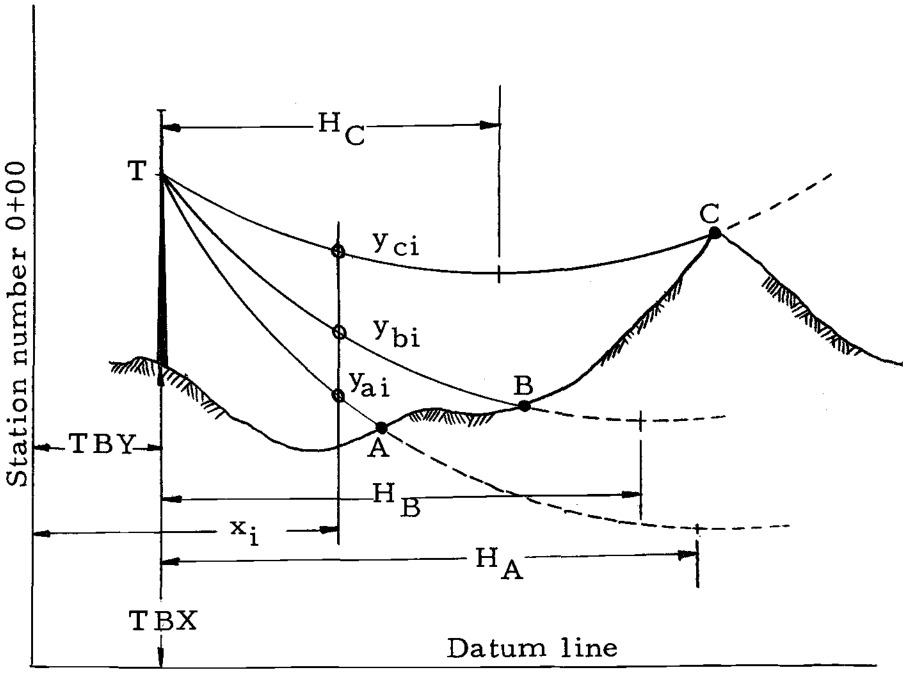
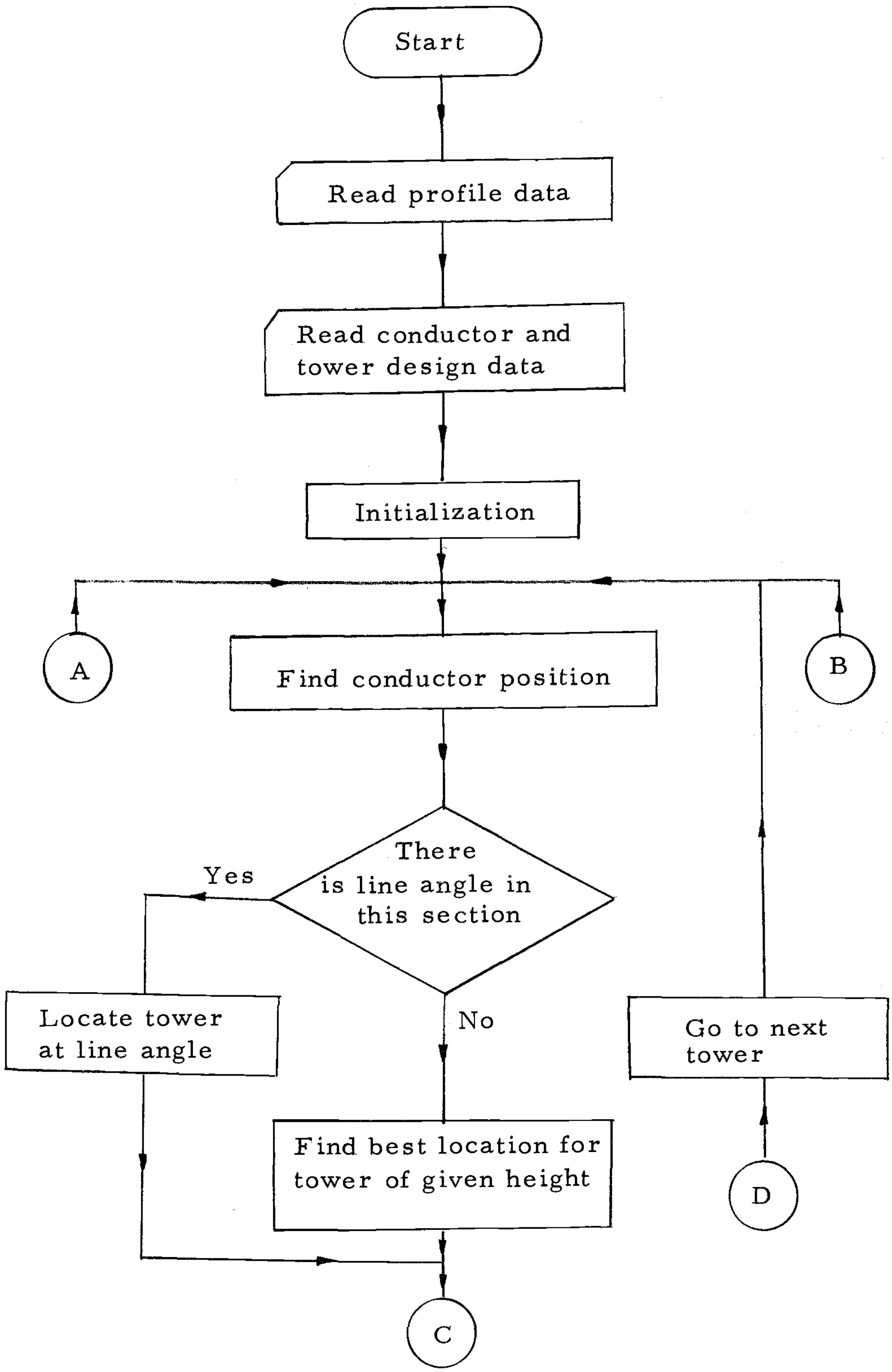
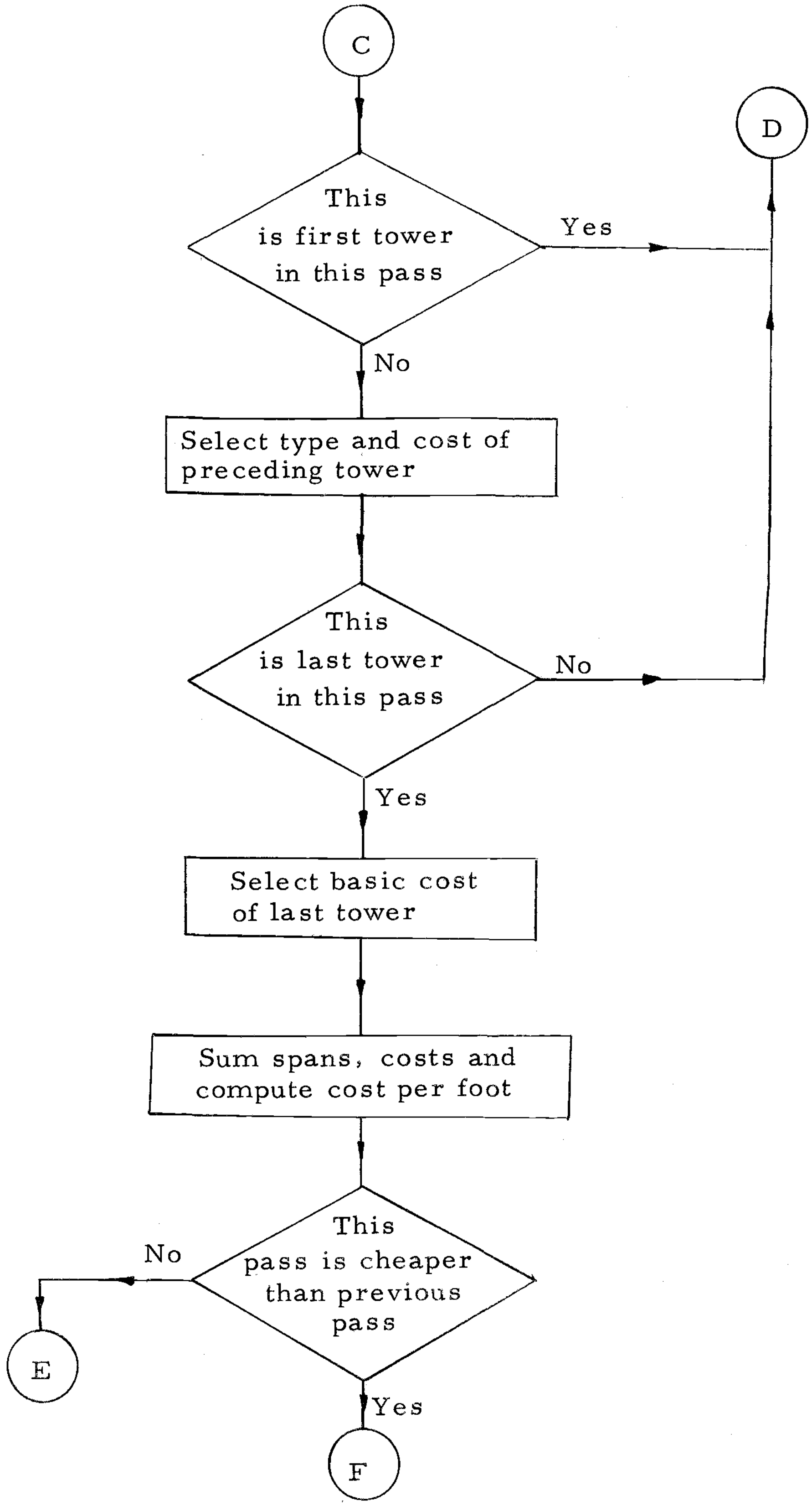


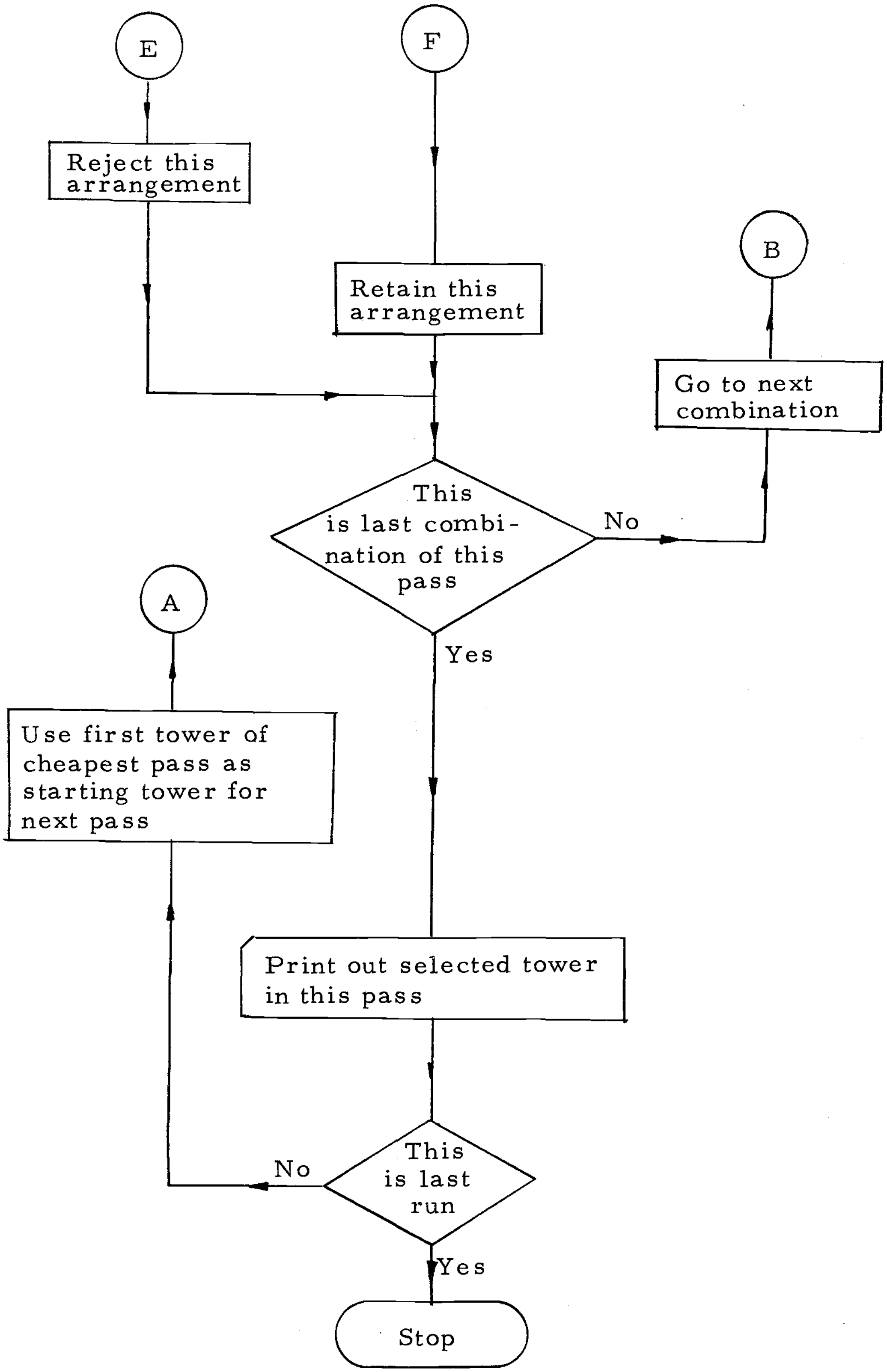
Figure 18. Curves of different axis of symmetries.

All variables on the right side are the same except y_{ai}, y_{bi}, and y_{ci}. Then it can be easily seen that if the value H_B is less than the value H_A, the value y_{bi} must then be greater than the value y_{ai}. In the same way, if the value H_C is less than H_B, then the value y_{ci} must be greater than the value y_{bi}. If there is still any curve that has the value of H less than the above curves, the Y ordinate or the elevation of that curve at the ordinate x_i must be higher. Therefore the curve that has a minimum value of H must be the curve that passes through one ground profile point and goes over all other points.

APPENDIX III.




C
D
This
is first tower
in this pass
Yes
No
Select type and cost of
preceding tower
This
is last tower
in this pass
No
Yes
Select basic cost
of last tower
Sum spans, costs and
compute cost per foot
This
pass is cheaper
than previous
pass
No
Yes
E
F


E
F
Reject this arrangement
Retain this arrangement
B
Go to next combination
This is last combination of this pass
No
Yes
A
Use first tower of cheapest pass as starting tower for next pass
Print out selected tower in this pass
This is last run
No
Yes
Stop