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Title TRANSMISSION LINE TOWER LOCATION ON NONFLAT TERRAIN BY DIGITAL COMPUTER METHODS

Abstract approved John F Engle

A method of locating electric transmission line towers using ground survey data in a digital computer program is presented in this thesis. The towers are located for maximum spacing subject to the constraints of available tower heights, forbidden ground areas, minimum ground clearance, and specified conductor tensions. The digital method eliminates the use of ground profile charts and sag templates.

An integral part of this thesis is the determination of conductor sag and tension from the catenary equation. These data can be obtained from the computer program as a function of support spacing for any desired conductor input data.

The complete program for tower location consists of several routines logically worked together to obtain the final result. These separate routines are: 1) The estimation of the initial span length based upon conductor data and desired ground clearance; 2) The determination of conductor end tensions including the effect of unequal support elevations; 3) The determination of the maximum sag relative to the two support points; 4) The relationship of ground

profile to conductor profile is calculated to determine the magnitude and point of minimum ground clearance. Linear interpolation is used between data points.

Several ground profile were tested. The results and a discussion of them are included in this thesis.

TRANSMISSION LINE TOWER LOCATION ON NONFLAT TERRAIN BY DIGITAL COMPUTER METHODS

by

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INTRODUCTION

Transmission lines are designed basically for maximum spans and minimum tower heights. Of the several factors involved in line design, the sag of the conductor and the tension in the conductor are the major constraints. Sag is affected by the length of span, the weight of the conductor including additional sleet or wind load, and the temperature. The temperature is an important factor because it effects the conductor length and hence the tension.

Manual methods of locating transmission line towers require line profile drawings and transparent sag templates. The method consumes considerable time in preparation and execution.

Computer methods developed recently have been used by some electric power utilities to locate transmission towers over varied terrain features. The process is much faster than the manual method and attempts are being made to include several factors for minimizing the total cost of the line.

A common procedure employed by these computer methods is the positioning of the conductor sag template so that at least minimum ground clearance is provided and a tower height is selected with a tower location that will support the conductor. More than minimum clearance will be provided if the exact required tower height is not available.

The location of transmission towers by the method presented in this thesis is performed by fitting a catenary curve to the computer preselected tower locations. Locations of towers are estimated on the basis of the tower heights, the design tension for nonflat terrain, and the specified minimum ground clearance. The sag and tension of a conductor are computed directly from the catenary curve. Ground clearance is checked at every survey station including the clearance at the lowest point of the conductor. Both the tower height and the span length are adjusted by the program until the best combination is obtained.

The computer program was written in the Symbolic Language Programming System for use on an IBM-1620 digital computer.

FACTORS GOVERNING DESIGN

Ruling Span

If all spans in a section of line between dead-ends are the same length, the formation of a uniform thickness of ice combined with a wind load will result in equal conductor tension in all spans. In practice span lengths will usually vary in any section of line with the result that the application of ice and wind loads will cause the conductor tension to become greater in the longer spans than in the shorter spans. A slight movement of the structures on which the conductor is supported will tend to equalize this unequal tension. Unless the conductor is strung to limit this condition, it is possible for the conductor tension in the longer spans to reach a value greater than desired. This is usually remedied by stringing the conductor on a ruling span basis.

A ruling span is a calculated span length for which the conductor tension, under changes in temperature and loading, best represents the average tension in the conductor in a particular series of spans between dead-ends. An approximate method of determining the ruling span in a section of line between dead-ends is to find the arithmetic average span length, and add to this 2/3 the difference between the longest span and the average span.

Theoretically the ruling span can be calculated accurately by summing up the cubes of all span lengths, dividing by the sum of the span lengths and then taking the square root of the quotient.

$$\text{Ruling span} = \left(\frac{s_1^3 + s_2^3 + \ldots s_n^3}{s_1 + s_2 + \ldots s_n} \right)^{\frac{1}{2}} .$$

Conductor Loading

The National Electrical Safety Code (NESC) specified the conductor loading as follows:

> The loading on conductors shall be assumed to be the resultant loading per foot equivalent to the vertical load per foot of the conductor, ice-covered where specified, combined with the transverse loading per foot due to a transverse, horizontal wind pressure upon the projected area of the conductor, ice-covered where specified, to which equivalent resultant shall be added a constant. The tabulation in Table I are the values for ice, wind, temperature, and constants which shall be used to determine the conductor loading.

The loading districts designated as heavy, medium, and light in the tabulation, are usually shown geographically on a general loading map.

TABLE I. ASSUMPTIONS ON CONDUCTOR LOADING

Assumed Loadings	Loading District		
	Heavy	Medium	Light
Radial thickness of ice (in.)	0.50	0.25	0
Horizontal wind pressure (lbs./sq. ft.)	4	4	9
Temperature (°F)	0	+15	+30
Constant to be added to the resultant in pounds per foot, for bare conductors of aluminum (with or without steel reinforcement)	0.31	0.22	0.05

These assumed ice and wind loadings provide the basis for calculating the resultant conductor load for all loading districts.

Ice Loading on Conductors

The ice loading of an aerial conductor as prescribed by the NESC, Rule 252, shall be computed for a radial thickness of ice of 0.50 inch for the heavy loading district, 0.25 inch for the medium, and no ice for the light loading district. The calculation of the weight of ice per foot of conductor assumes the weight of ice to be 57 pounds per cubic foot.

No allowance is made for ice formation in the interstices of bare stranded or cabled conductor. The calculations for ice loading assume the ice covering to be a uniform tube with a wall thickness of t inches and an inside diameter equal to the outside diameter of the conductor. The formula for ice load based on these assumptions is given as follows:

$$\text{Ice load} = 1.244\, t(d_1+t) \qquad \text{(lbs./ft. of conductor)}$$

where d_1 is the conductor diameter in inches.

Wind Loading on Conductors

The values of wind pressure (p_1) in pounds per square foot of the projected area can be obtained from the values of actual wind velocity by the relation:

$$p_1 = 0.0025\ V_a^2 \qquad \text{(lbs./sq. ft.)}$$

where V_a is the actual wind velocity in miles per hour.

The wind load on a conductor is calculated from the wind pressure and the projected area of the conductor by the formula

$$\text{wind load} = p_1 \cdot \frac{d_1}{12} \cdot L \qquad \text{(lbs.)}$$

or

$$\text{wind load} = \frac{p_1 d_1}{12} \qquad \text{(lbs./ft. of conductor)}$$

where L is the length of conductor in feet.

Where the conductor is loaded with ice, the projected area is increased by the top and bottom thickness of the covering of ice. Calculations for the wind load on this greater projected area assume the thickness of ice coating to be uniform and concentric with the conductor. With these assumptions the relation for wind load on a conductor with a radial covering of ice t inches in thickness is given by the formula:

$$\text{wind load} = p_1 \cdot \frac{(d_1 + 2t)}{12} . \qquad \text{(lbs./ft. of conductor)}$$

Combined Ice and Wind Load on Conductors

To arrive at a total resultant conductor load from the ice load, wind load, and conductor weight, the various loads are added vectorially. Figure 1 shows the relationship of all these forces acting on the conductor. Figure 2 shows the step-by-step vector addition of these loads.

The ice and wind loads form the basis for preliminary calculations of sag and tension data. From these conductor loadings and the prescribed conductor tension limits, sag and tension charts are prepared by the graphical method. These charts establish the relationship between conductor sag and tension for a range of span lengths at several temperatures.

The tension to which a conductor is strung should be such that when the assumed maximum ice and wind load is applied the stress will not exceed limits established and considered safe by appropriate regulating authorities, for example, the NESC specified that the maximum tension shall be not more than 60 percent of the ultimate tensile strength of the conductor.

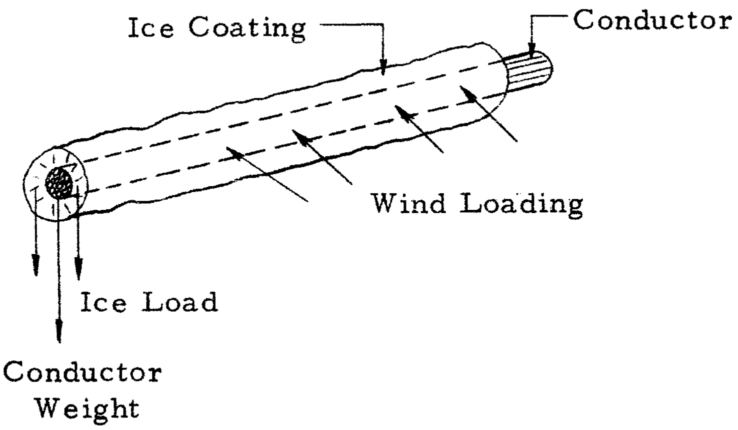

Figure 1. Combined load on a conductor.

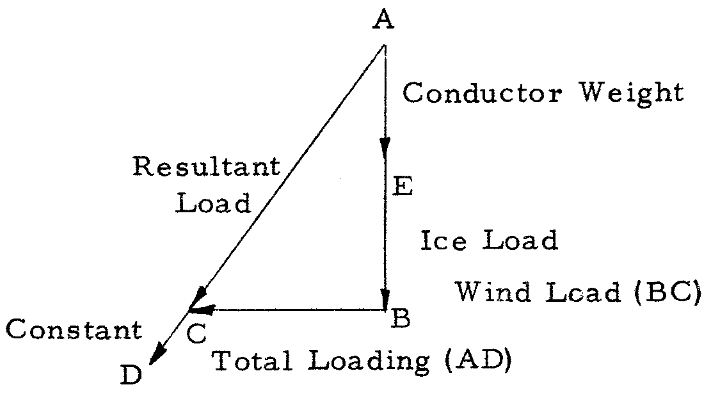

Figure 2. Vector diagram.

SAG-TENSION CALCULATION

In order to specify the tension to be used in stringing transmission line conductors, the values of sag and tension for winter and summer conditions must be known. The conductor tension in the winter caused by ice and wind loading and the contraction of the conductor at low temperature should not be so great as to overstrain the conductor. In summer, the sag should not increase so much that the conductor comes below the minimum distance above the ground.

A transmission-line conductor stretched between two supports takes the shape of a catenary, which is the curve of a chain hung or stretched between two supports.

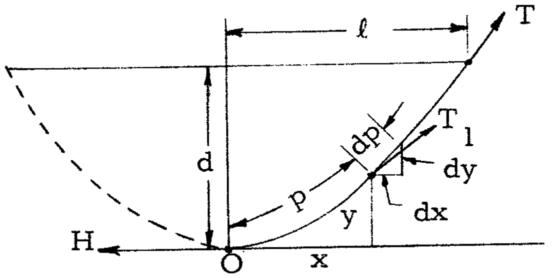

Figure 3. Diagram of a catenary curve.

In Figure 3, O is the lowest point of a conductor between two supports that are at equal heights. At point O the conductor is horizontal. Let O be the origin of coordinates. Consider a portion of the conductor of length p, measured from O. This portion is held in place by the tensions H and T_1 at the two ends. At the right-hand end of p, the horizontal component of the tension is equal and opposite to H, the tension at O. The vertical component of the tension T_1 is equal and opposite to the sum of the vertical forces on the portion of conductor, namely wp, where w is the weight per unit length of the cable, including its ice loading if any. The resultant tension is in the direction of the cable and of dp, and the triangle of forces has the same shape as the triangle of dx and dy.

Therefore

$$\frac{dy}{dx} = \frac{wp}{H}$$

where w and H are constants, and

$$dp^2 = dx^2 + dy^2$$

$$dp = \left[1 + \left(\frac{dy}{dx}\right)^2\right]^{\frac{1}{2}} dx$$

$$dp = \left(1 + \frac{w^2p^2}{H^2}\right)^{\frac{1}{2}} dx \;. \qquad (1)$$

Let $\frac{wp}{H} = z$, then $p = \frac{H}{w} z$

$$dx = \frac{H}{w} \frac{dz}{(1 + z^2)^{\frac{1}{2}}} \;.$$

This is a differential equation in which the variables have been separated. Each side may be directly integrated

$$x = \frac{H}{w} \sinh^{-1} z + c = \frac{H}{w} \sinh^{-1} \frac{wp}{H} \;.$$

The constant of integration c is zero because $x = 0$ when p or $z = 0$. Then,

$$\frac{wp}{H} = \sinh \frac{wx}{H} = \frac{dy}{dx} \qquad (2)$$

from the first line of this computation. From this

$$p = \frac{H}{w} \sinh \frac{wx}{H}$$

and also

$$\sinh \frac{wx}{H} dx = dy.$$

Integrating both sides,

$$y = \frac{H}{w} \cosh \frac{wx}{H} + c_1 \ .$$

Put $y = 0$, then $x = 0$, and $0 = \frac{H}{w} + c_1$, since, by the series, $\cosh \ 0 = 1$. Therefore

$$y = \frac{H}{w} (\cosh \frac{wx}{H} - 1).$$

Let T_1 be the tension at the end of p. From the triangle of forces already considered,

from (1) $$\frac{T_1}{H} = \frac{dp}{dx} = \left(1 + \frac{w^2 p^2}{H^2}\right)^{\frac{1}{2}}$$

from (2) $$\frac{T_1}{H} = \left(1 + \sinh^2 \frac{wx}{H}\right)^{\frac{1}{2}}$$

since $\cosh^2 M - \sinh^2 M = 1$.

At the support, x becomes ℓ, the half-span; y becomes d, the depth of sag; and T_1 becomes T, the greatest tension in the conductor. The equations become

$$2P = 2\frac{H}{w}\sinh\frac{w\ell}{H} = 2\ell\left[1 + \frac{1}{6}\left(\frac{w\ell}{H}\right)^2 + \frac{1}{120}\left(\frac{w\ell}{H}\right)^4 + \dots\right]$$

and

$$d = \frac{H}{w}\left(\cosh\frac{w\ell}{H} - 1\right) = \ell\left[\frac{1}{2}\left(\frac{w\ell}{H}\right) + \frac{1}{24}\left(\frac{w\ell}{H}\right)^3 + \dots\right].$$

The tension in the conductor at the support is

$$T = H\cosh\frac{w\ell}{H} = H\left[1 + \frac{1}{2}\left(\frac{w\ell}{H}\right)^2 + \frac{1}{24}\left(\frac{w\ell}{H}\right)^4 + \dots\right].$$

Accuracy of Hyperbolic Approximation in Sag-Tension Calculations

Hyperbolic functions are involved in the calculations of sag and tension for overhead electric line construction.

Let w = total loading on conductor

$$= \left[\{x + 1.244\, t(d_1 + t)\}^2 + \{\tfrac{1}{12}\, p_1(d_1 + 2t)\}^2\right]^{\frac{1}{2}} + C \quad (\text{lbs./ft.})$$

where x = conductor weight (lbs./ft.)

d_1 = conductor diameter (in.)

t = radial thickness of ice (in.)

p_1 = wind pressure (lbs./sq. ft.)

C = a constant to be added according to the NESC. (lb./ft.)

The perimeter of a conductor is defined as the length of the conductor measured along the catenary curve. Using the following designations,

2ℓ = span length (ft.)

H = horizontal tension (lbs.)

d = sag (ft.)

$2P$ = perimeter of a conductor. (ft.)

the formulas for the perimeter and sag of a conductor become

$$2P = 2\frac{H}{w}\sinh\frac{w\ell}{H} = 2\ell\left[1 + \frac{1}{6}\left(\frac{w\ell}{H}\right)^2 + \frac{1}{120}\left(\frac{w\ell}{H}\right)^4 + \ldots\right] \tag{3}$$

$$d = \frac{H}{w}\left(\cosh\frac{w\ell}{H} - 1\right) = \ell\left[\frac{1}{2}\left(\frac{w\ell}{H}\right) + \frac{1}{24}\left(\frac{w\ell}{H}\right)^3 + \ldots\right]. \tag{4}$$

The approximations of the above equations are

$$2P = 2\ell\left[1 + \frac{1}{6}\left(\frac{w\ell}{H}\right)^2\right] \tag{5}$$

and

$$d = \frac{1}{2}\left(\frac{w\ell^2}{H}\right). \tag{6}$$

In order to reduce the computing time to a minimum in the successive computations a computer program was written to determine the accuracy of the relationships in equation (3) as compared with equation (5) and equation (4) as compared with equation (6).

Two conductors are chosen from the Conductor Data Table (4, p. 92). They are both ACSR 795 Mcm and 1,780 Mcm. The maximum tension is 50 percent of the ultimate tensile strength of the conductor. In checking the accuracy, any loading conditions could be used. The results are shown in Table II on page 14. It is obvious that approximate formulas can be used without reducing the accuracy.

TABLE II. ACCURACY OF APPROXIMATE FORMULAS IN COMPUTING SAG AND PERIMETER OF CONDUCTOR

Conductor 795 Mcm. ACSR.

Design Tension = 50 percent ultimate strength

SPAN	PERI1	PERI2	SAG1	SAG2
100	100.00019	100.00020	.08698	.08766
200	200.00161	200.00162	.34936	.35064
300	300.00547	300.00552	.78855	.78894
400	400.01305	400.01308	1.40171	1.40256
500	500.02556	500.02560	2.19027	2.19150
600	600.04417	600.04422	3.15564	3.15576
700	700.07023	700.07028	4.29499	4.29535
800	800.10484	800.10488	5.60972	5.61025
900	900.14926	900.14931	7.09985	7.10048
1000	1000.20480	1000.20490	8.76680	8.76602
1100	1100.27260	1100.27260	10.60771	10.60689
1200	1200.35400	1200.35400	12.62402	12.62307

Conductor 1,780 Mcm. ACSR.

Design Tension = 50 percent ultimate strength

SPAN	PERI1	PERI2	SAG1	SAG2
100	100.00023	100.00024	.09562	.09673
200	200.00197	200.00198	.38636	.38694
300	300.00669	300.00672	.86964	.87061
400	400.01591	400.01596	1.54675	1.54776
500	500.03111	500.03115	2.41768	2.41837
600	600.05383	600.05388	3.48244	3.48246
700	700.08549	700.08554	4.73974	4.74001
800	800.12771	800.12776	6.19087	6.19104
900	900.18186	900.18189	7.83583	7.83554
1000	1000.24940	1000.24950	9.67461	9.67350
1100	1100.33200	1100.33200	11.70594	11.70494
1200	1200.43110	1200.43110	13.93108	13.92985

$$\text{PERI1} = 2\frac{H}{w}\sinh\frac{w\ell}{H} \qquad \text{(exact formula)}$$

$$\text{PERI2} = 2\ell\left[1 + \frac{1}{6}\left(\frac{w\ell}{H}\right)^{2}\right] \qquad \text{(approximate formula)}$$

$$\text{SAG1} = \frac{H}{w}\left(\cosh\frac{w\ell}{H} - 1\right) \qquad \text{(exact formula)}$$

$$\text{SAG2} = \frac{1}{2}\left(\frac{w\ell^{2}}{H}\right) \qquad \text{(approximate formula)}$$

Stretch of the Conductor

When a hard, elastic metal of length 2ℓ is stressed by a tension, its elongation, if within the elastic limit, is proportional to the tension and is

$$2\ell \frac{T}{AE}$$

where A is the area of the cross section, and

E is a constant for the metal, called the modulus of elasticity.

The unstressed length is the length the conductor would have if it were disconnected from the supports and laid on a horizontal roadway. It is equal to the perimeter minus the stretch.

Let Lu be the unstressed length, then

$$Lu = 2P - 2\ell \frac{T}{AE} \tag{7}$$

or

$$Lu = 2\ell \left(1 + \frac{1}{6} \frac{w^2 \ell^2}{T^2}\right) - 2\ell \frac{T}{AE}$$

and putting $T = \dfrac{w\ell^2}{2d}$,

then

$$Lu = 2\ell \left(1 + \frac{2}{3} \frac{d^2}{\ell^2}\right) - \frac{w\ell^3}{AEd} . \tag{8}$$

Sag-Tension Charts

Sag and tension charts are based on the conductor tension limits specified in the line design. These limits depend on the type of conductor, the line, grade of construction, and any other special requirements.

Let Lu = unstressed length of the conductor at any given initial temperature

Lu' = unstressed length of the conductor at final temperature

t_i = initial temperature

t_f = final temperature

α = coefficient of expansion, characteristic of the material composition of the cable.

Then the relationship between Lu' and Lu due to the influence of changes in temperature is

$$Lu' = Lu\left[1 + \alpha(t_f - t_i)\right] . \tag{9}$$

Therefore, knowing the conductor data of a specific temperature and a given span length, the value of Lu can be calculated using the approximate catenary formulas, equation (5) and (7). The value of Lu' can then be determined for any temperature through the use of equation (9). The tension and sag corresponding to the new temperature can be determined by substituting the value of Lu' into equations (7) and (8) in place of Lu.

Equations (7) and (8) are rearranged for the solution of tension and sag through the following derivations.

$$Lu' = 2\ell\left[1+\frac{1}{6}\left(\frac{w\ell}{T}\right)^2\right] - 2\ell\frac{T}{AE}$$

$$Lu' = 2\ell + \frac{w^2\ell^3}{3T^2} - \frac{2\ell T}{AE}$$

$$Lu' = 2\ell + \frac{w^2\ell^3AE - 6\ell T^3}{3AET^2}$$

$$3AET^2(Lu'-2\ell) = w^2\ell^3AE - 6\ell T^3$$

or

$$6\ell T^3 + 3AE(Lu' - 2\ell)T^2 - w^2\ell^3AE = 0. \tag{10}$$

For the corresponding sags at any temperatures

$$Lu' = 2\ell\left(1+\frac{2}{3}\frac{d^2}{\ell^2}\right) - \frac{w\ell^3}{AEd}$$

$$= 2\ell + \frac{4d^2}{3\ell} - \frac{w\ell^3}{AEd}$$

$$(Lu'-2\ell) = \frac{4AEd^3 - 3w\ell^4}{3\ell AEd}$$

$$3\ell AEd(Lu'-2\ell) = 4AEd^3 - 3w\ell^4$$

$$4AEd^3 - 3\ell AE(Lu'-2\ell)d - 3w\ell^4 = 0.$$

or

$$d^3 - \frac{3}{4}\ell(Lu'-2\ell)d - \frac{3}{4}\frac{w\ell^4}{AE} = 0. \tag{11}$$

Equations (10) and (11) can be solved by any method but since there is one value of tension between T = 0 and T = Tmaximum that is specified in the design criterion, there is only one value of sag (d) corresponding to the tension (T). It is obvious that only one positive real root is required from each of equations (10) and

(11) and this simplifies the computations.

An example of sag-tension charts computed by a digital program for 795 Mcm all aluminum conductor (Lilac) based on maximum design tension 7, 170 lbs. and medium loading condition are shown in Figure 4.

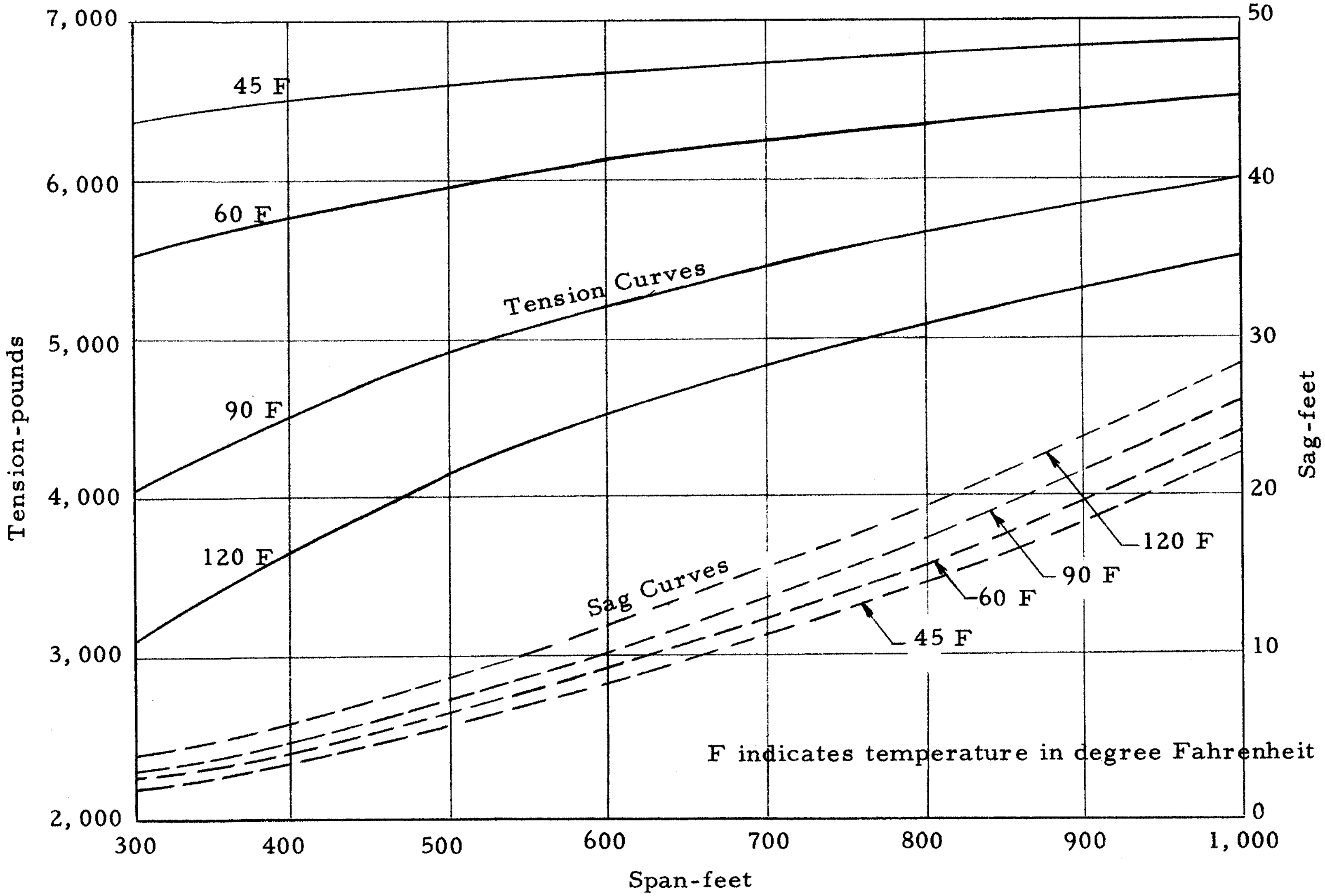

Figure 4. Sag-tension chart for 795 Mcm all aluminum conductor.

TRANSMISSION TOWER LOCATION

The steps used in developing the computer method for locating transmission towers on nonflat terrain are described in the following sections.

Estimated Span Length

A straightforward method is used to estimate a span length from the basic formula

$$d = \frac{wS^2}{8T} \tag{12}$$

where d = sag of a conductor

S = span length

T = tension in a conductor

w = resultant weight of a conductor.

Then equation (12) may be written as

$$S = \left(\frac{8dT}{w}\right)^{\frac{1}{2}} .$$

POLEA and POLEB are symbolic names representing the height of pole A and pole B respectively. The height of a pole is defined as the height of the lowest suspending phase conductor above the tower base. Then

$$\text{The average pole height} = \frac{1}{2}\ (\text{POLEA} + \text{POLEB})$$

and

$$\text{Maximum sag} = \text{the average pole height} - \text{minimum ground clearance}$$

Thus the estimated span is

$$S = \left(\frac{8 \cdot \text{Maximum sag} \cdot T}{w} \right)^{\frac{1}{2}} .$$

Inclined Span Sag Calculations

Where the terrain is such that the conductor supports are not at the same level, the sag does not correspond to the sag given for a level ground span on regular sag and tension charts.

These sags are calculated from inclined span sag formulas which express the relation between the parameters shown in Figure 5.

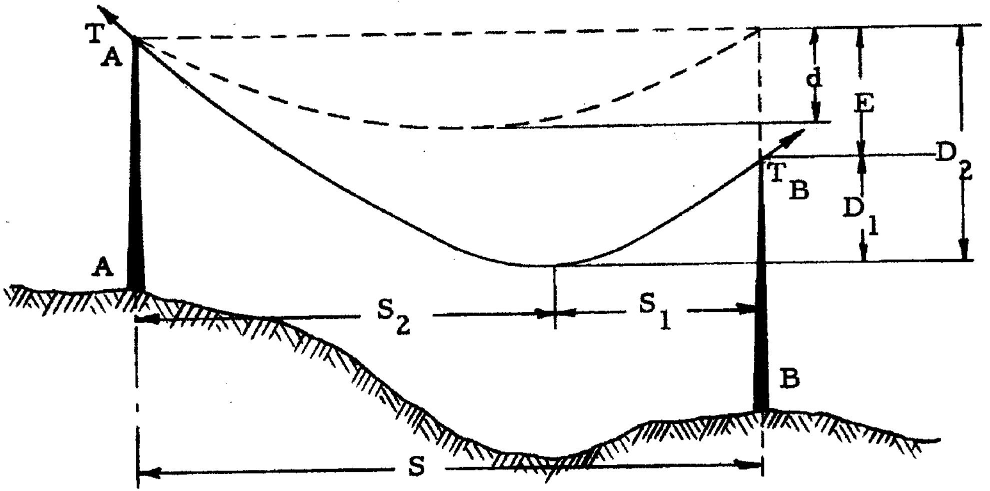

Figure 5. The inclined span catenary.

Basically the sag in a level span is $d = \frac{wS^2}{8T}$ and

$$D_1 = d\left(1 - \frac{E}{4d}\right)^2$$

$$D_2 = d\left(1 + \frac{E}{4d}\right)^2$$

$$S_1 = \frac{S}{2}\left(1 - \frac{E}{4d}\right)$$

$$S_2 = S - S_1 .$$

If $(1 - \frac{E}{4d})$ is negative the theoretical low point of the conductor will be past the lower support, i. e. "uplift" will exist at the lower support.

Inclined Span Tension Calculations

Let T_A and T_B be the tensions at tower A and B respectively. Then

$$T_A = \frac{w(2S_2)^2}{8d} = \frac{0.5w\,(S_2)^2}{d} \tag{13}$$

and

$$T_B = \frac{w(2S_1)^2}{8d} = \frac{0.5w(S_1)^2}{d} \; . \tag{14}$$

For level span $S_1 = S_2 = \frac{S}{2}$, hence from equation (13) and (14)

$$T_A = \frac{0.5w(\frac{S}{2})^2}{d}$$

and

$$T_B = \frac{0.5w(\frac{S}{2})^2}{d}$$

or simply $T_A = T_B$, which means that tensions in the conductor at both towers are equalized.

Method of Checking Ground Clearance

When the second pole (pole B) is located and the tensions T_A and T_B are calculated, the maximum sag, for example, the sag at the hottest temperature is calculated and D_1, S_1 become known. Since the conductor curve is represented by

$$y = kx^2$$

or

$$k = \frac{y}{x^2}$$

then

$$k = \frac{D_1}{S_1^2} \tag{15}$$

and the general equation is

$$y = \frac{D_1}{S_1^2} \cdot x^2. \tag{16}$$

Knowing the relationship between the horizontal distance (x) and the vertical distance (y) the ground clearance is checked at each of the survey stations between the two poles.

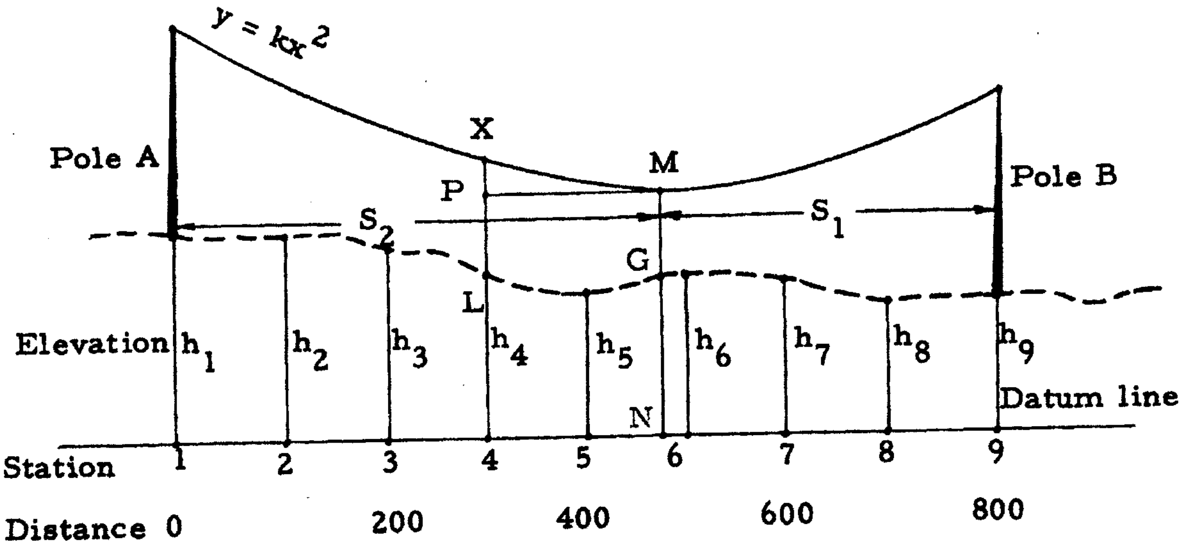

Figure 6. Method of checking ground clearance.

For example, to find the ground clearance at a point X at survey station number 4,

$$MP = S_2 - 300 = x$$

$$XP = k(MP)^2 = y$$

or

$$XP = k(S_2 - 300)^2.$$

Since MN is known, and

$$PL = MN - h_4$$

then

$$XL = PL + XP$$

which is the ground clearance at survey station number 4.

To determine a ground clearance at point M, the minimum point of the catenary curve, where M lies between two survey stations, the elevation GN is determined by the method of linear interpolation.

Computer Program

The computer program is divided into a main program and several routines which provide the mathematical processes for locating the transmission towers.

Main Program. The main program requires two sets of input data. The first set includes the minimum ground clearance and conductor constants and the conductor loading data. The second set is the profile values which are read into the computer as discrete values of survey station, elevation and distance.

Routine Number 1. Assume the first tower is to be located at the data starting point. A span length is then estimated and a temporary tower is located.

Routine Number 2. Tension at both towers is computed and checked with the maximum allowable design tension.

Routine Number 3. The maximum sag of the inclined span is computed.

Routine Number 4. Ground clearance is checked at each survey station to ensure that the minimum ground clearance as specified by the safety rule is maintained.

Routine Number 5. After a tower is located the process is repeated again to locate successive towers.

Adjusting Routines. Adjusting for the maximum span with the lowest possible tower height is the main purpose of these routines. These adjusting routines provide the use of higher towers when the minimum tower height could not maintain the minimum ground clearance. Whenever the ground clearance is more than the minimum specified value the span length is increased within the constraint of maximum allowable tension.

Special Features and Modification

The program is written in the Symbolic Language Programming

System for use on an IBM-1620 digital computer and requires 9492 core storage locations of which 1600 core storage locations are reserved for storing approximately one mile of profile data. For the standard capacity machine with 20,000 core storage locations, a test can be made for a line extending nearly five miles.

The program allows for a change in conductor type, conductor loading conditions, ground clearance and initial tower heights. Equal profile intervals are not necessary. Any profile breaks (terrain deviations that do not conform to the base increment, e.g., 50 ft. interval) may be included. The ground clearance is checked at every survey station, especially, at the lowest point of the catenary curve where a method of linear interpolation is used to determine the elevation of the terrain underneath.

The method of checking the ground clearance at every survey station enables the program to be modified for the case where the new transmission line will cross an existing line.

There may be many locations on a terrain that prohibit the locating of transmission towers, such as river crossings. The profile data is then modified. Suppose the elevation of tower A is 0625.00 ft. above the datum line and the elevation at location B, which prohibits tower locating, is 0600.00 ft. Then the elevation at location B is modified to 9600.00 ft. The computer will compare both tower top elevations if the second tower is to be located at location B. The absolute value of the difference in elevations will be | 9600.00 - 0625.00 | or 8975.00 ft. instead of | 0625.00 - 0600.00 | or 25.00 ft. and thus location B is not used. It is obvious that after the modification the difference in elevations will be much higher than for the case where there is an uplift condition of the conductor. The computer can distinguish the latter case from the former. The ground clearance check for the modified elevation as described above may be done by eliminating the modified data and using the actual elevation.

Problems of locating a tower at a corner or dead-end point can also be solved by using the modified profile data. The computer should locate several towers as usual; but each time a tower is located, the distance from that tower to the preselected location for a specially designated tower is compared to a specified longest possible span for the available tower heights. Whenever the distance is shorter than the specified maximum span the next tower to be located is at the preselected location. If this remaining distance is less than the estimated span length, the last tower location is rejected. This tower is then relocated so that the new location is approximately half way between the previously located towers and the specially designated tower. Tension and ground clearance calculations are performed as usual for the two spans.

Evaluation of Results

A test on a 6,000 ft. diverse terrain was made. The minimum height of towers was 50 ft. and tower A, which was the first tower, was located at a starting point (point 1 in Figure 7). The computer estimated a span length of 714.684 ft. and located a tower called temporary tower B at point X, a distance of 750 ft. from Tower A.

The tension at towers A and B was computed and then checked with the maximum allowable design tension. Next, the inclined span sag at the hottest temperature was computed and the ground clearance was checked at each survey station between the towers. The minimum ground clearance was specified to be 30 ft. at the beginning of the program but this condition was less than 30 ft. The elevations of point 1 and X are compared and the height of tower B was increased to 55 ft. The computation process was repeated again and again until the height of tower B was 85 ft. At this height the minimum ground clearance was maintained and the tower height was said to be optimized.

When the tower height was optimized the span was increased to the distance of the next survey station, which was 800 ft. from tower A, and the computation process was repeated. It was found that the tension at towers A and B were 1,382 and 6,817 lbs. respectively and the minimum ground clearance was 34.96 ft.

The span length was increased again to the distance of the next survey station which was 850 ft. from tower A. At this location the tension at tower A was 1536 lbs. while that at tower B was 6,489 lbs. which is 45 percent of the ultimate strength of the conductor. The minimum ground clearance was 31.69 ft. All results were within the specified limits, so the computer increased the span length and used the distance of the next survey station. Tensions were computed and they were within the design limit, but the ground clearance exceeded the minimum requirement, and an attempt to locate a tower at this point was rejected. The computer selected the previous location and located tower B at a distance of 850 ft. from tower A. When this was done the span length was optimized.

The computer process continued with tower B as a starting point and located towers C, D, etc. until all the profile data was used.

The computer results for locating towers over a 6,000 ft. diverse terrain (120 survey stations) and over a 5,000 ft. relatively smooth terrain are summarized in Appendix II. Figures 7 and 8 illustrate the difference in selections made by the computer. It is shown that different tower heights can be used to fit a given ground profile and at some locations guying may be needed.

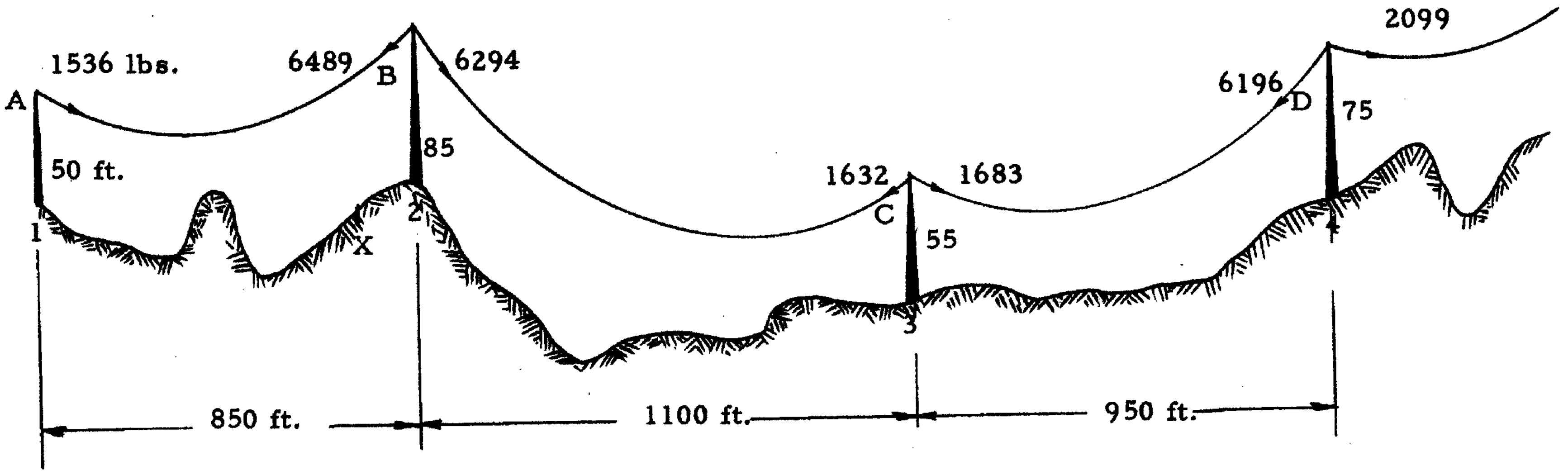

Figure 7. Tower locating on diverse terrain.

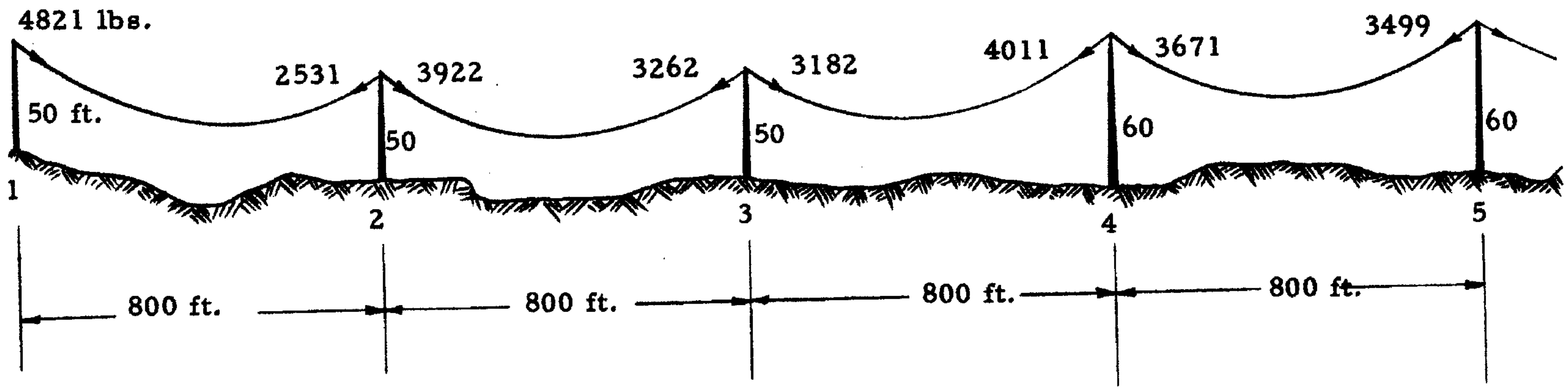

Figure 8. Tower locating on relatively smooth terrain.

CONCLUSION

Transmission towers can be selected to fit a line profile by digital computer methods. The investigation of the computer program has shown that it is possible to use the digital computer as a planning and design tool by transmission system engineers.

The advantage of locating the transmission line towers on non-flat terrain by a digital computer is the savings in time. It also permits a variety of preliminary designs and cost comparisons to be made.

As a result of positioning transmission towers over a diverse terrain, it has been shown that different tower heights are used and the spans are not necessary equal. A similar test on relatively smooth terrain has shown that the spans tend to have the same length although unequal tower heights are selected by the computer.

The computer program, written in a straightforward method, gives fundamental principle and numerical approach to the transmission tower location problems. It should be useful to electrical transmission students as well as transmission line engineers.

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APPENDIX I

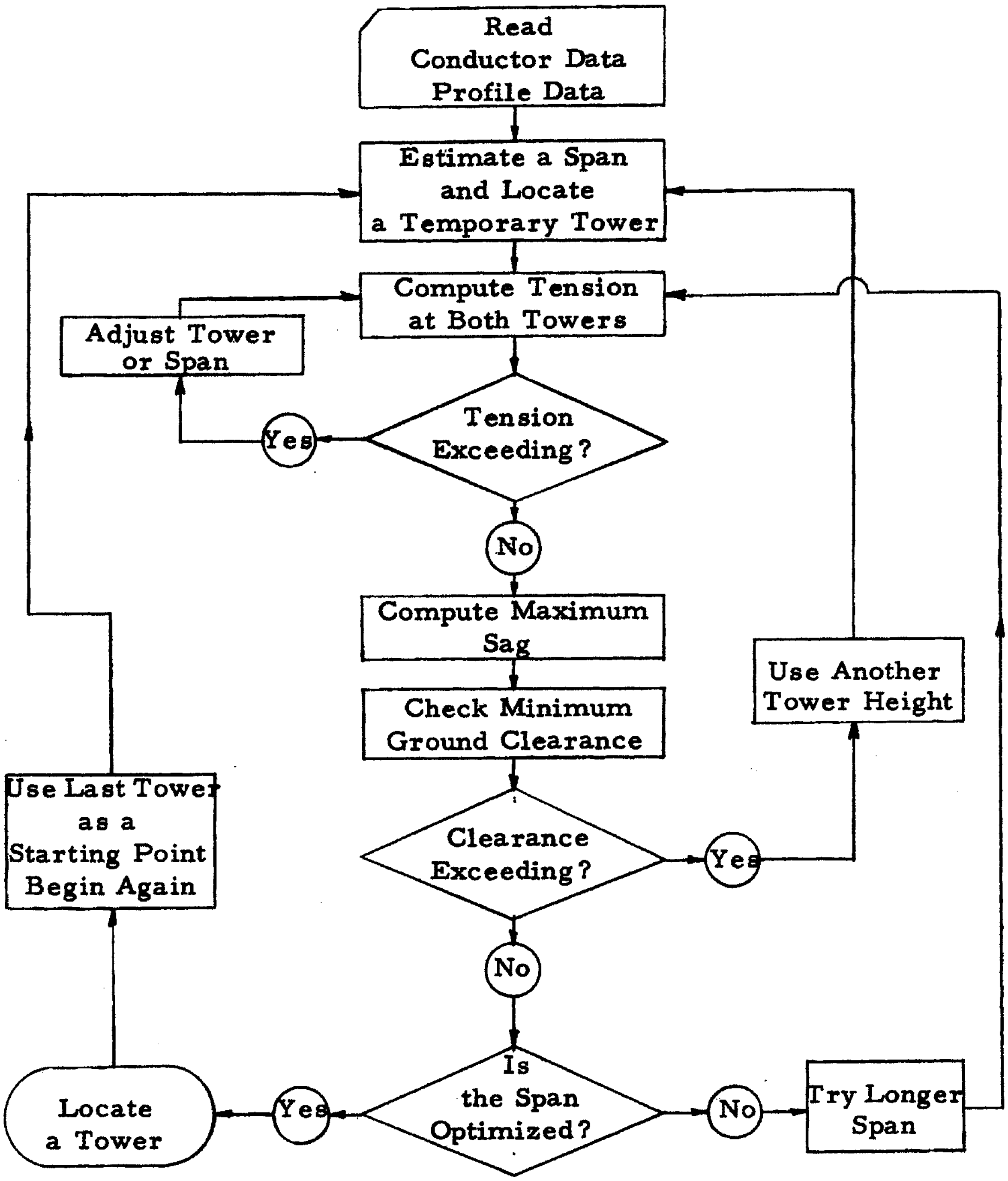


Figure 9. General flow chart for transmission line tower location.

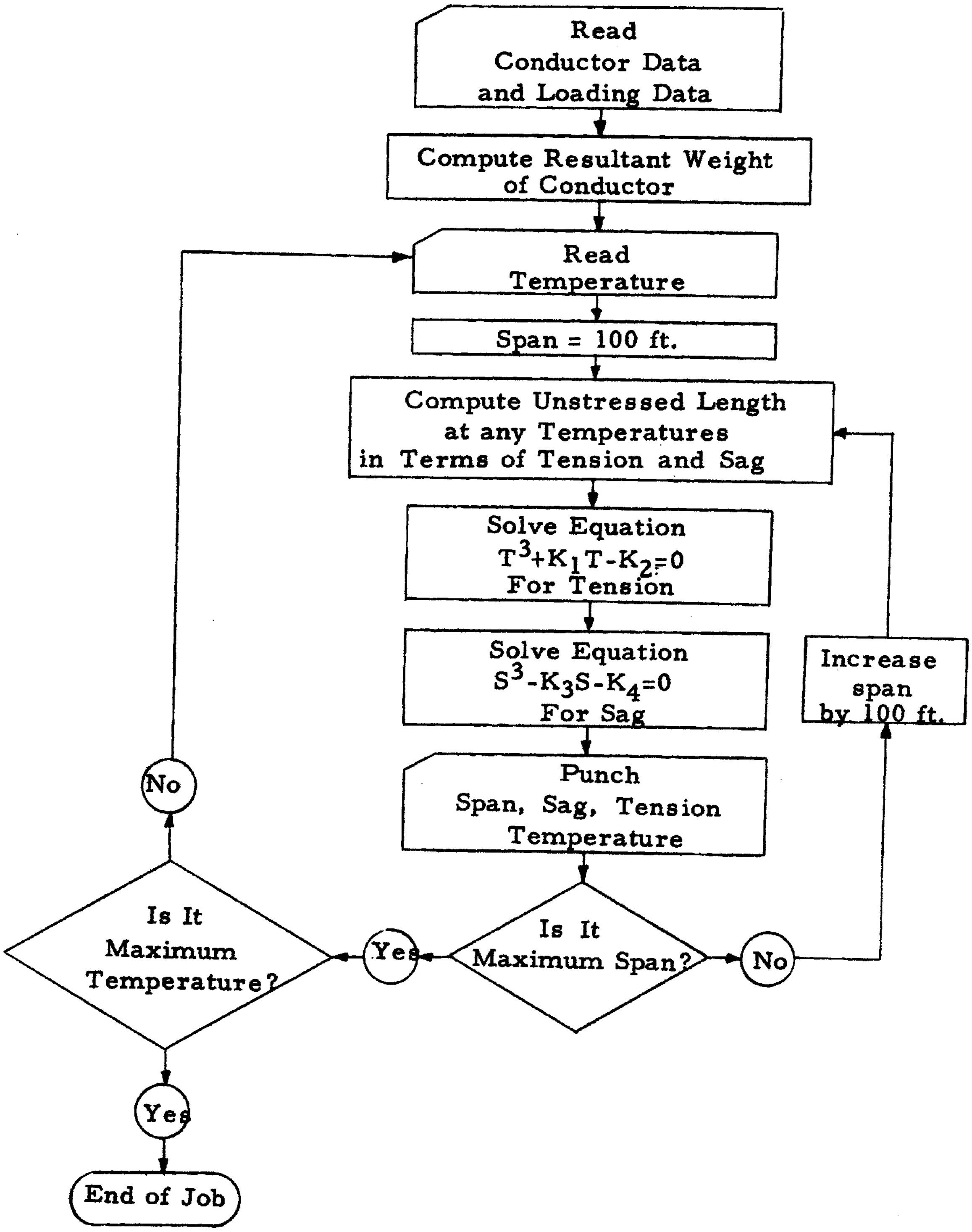


Figure 10. Flow chart for sag-tension computation.

APPENDIX II

DATA AND COMPUTER RESULTS

Data

Conductor	
Size	795 Mcm all aluminum
Diameter	1.0278 in.
Cross section area	0.6244 sq. in.
Ultimate strength	14,340 lbs.
Maximum design tension	7,170 lbs.
Modulus of elasticity	10,000,000 lbs./sq. in
Coefficient of linear expansion	0.00000128 in./in./°F
Temperature	
Minimum	32 °F
Maximum	120 °F
Wind pressure	8 lbs./sq. ft.
Minimum ground clearance	30 ft.

Computer Results

Computer results are summarized and shown in Table III and IV for a test on diverse terrain and another test on relatively smooth terrain.

TABLE III. SUMMARIZED COMPUTER RESULT OF A TEST ON DIVERSE TERRAIN

Tower Number	Survey Station	Tower Base Elevation (ft.)	Distance (ft.)	Estimated Span (ft.)	Actual Span (ft.)	Tower Height (ft.)	Tower Tension		Ground Clearance (ft.)
							Left (lbs.)	Right (lbs.)	
1	0100	0250.00	02000.0	---	--	50	--	1536	
									31.69
2	0117	0254.10	02850.0	714.684	850.0	85	6489	6294	
									31.47
3	0140	0222.50	03950.0	978.622	1100.0	55	1632	1683	
									30.68
4	0159	0247.00	04900.0	758.037	950.0	75	6196	2099	
									35.09
5	0179	0245.00	05850.0	911.047	950.0	100	5465	6732	
									33.19
6	0200	0213.30	07000.0	1072.027	1150.0	55	1420	3975	
									30.73
7	0216	0203.00	07800.0	758.037	800.0	60	3215	--	

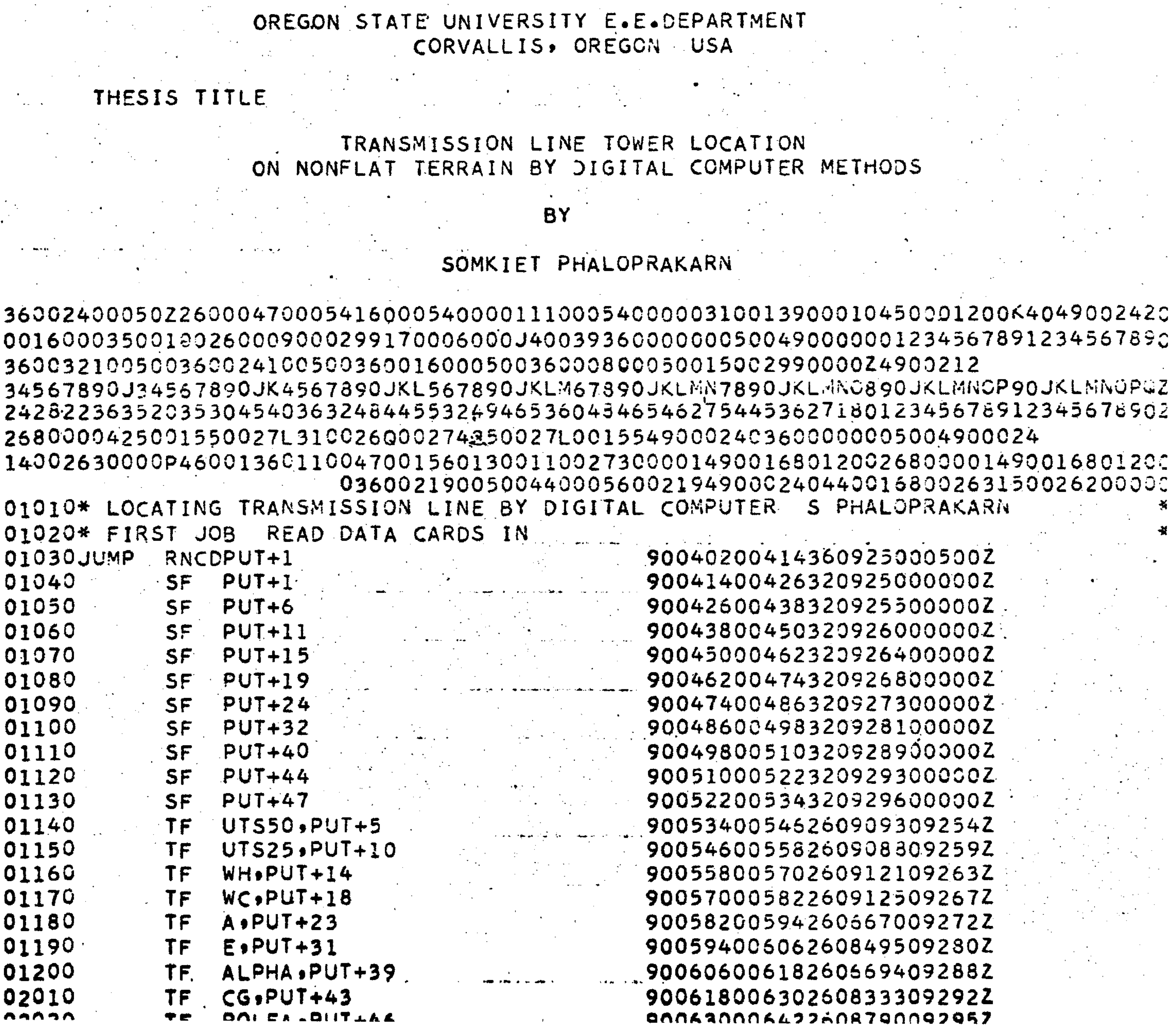
Total Length 6,000ft.

TABLE IV. SUMMARIZED COMPUTER RESULT OF A TEST ON RELATIVELY SMOOTH TERRAIN

Tower Number	Survey Station	Tower Base Elevation (ft.)	Distance (ft.)	Estimated Span (ft.)	Actual Span (ft.)	Tower Height (ft)	Tower Tension Left (lbs.)	Tower Tension Right (lbs.)	Ground Clearance (ft.)
1	0100	0250. 00	02000. 0	---	---	50	--	4821	
									31. 42
2	0116	0234. 00	02800. 0	714. 684	800. 0	50	2531	3922	
									32. 95
3	0133	0229. 40	03600. 0	714. 684	800. 0	50	3262	3182	
									30. 50
4	0149	0225. 20	04400. 0	714. 684	800. 0	60	4011	3671	
									30. 32
5	0165	0224. 00	05200. 0	799. 042	800. 0	60	3499	3606	
									32. 37
6	0182	0228. 70	06000. 0	799. 042	800. 0	55	3563	3914	
									31. 73
7	0196	0214. 20	06800. 0	758. 037	800. 0	65	3269	--	

Total Length 5, 000 ft.

Sample of the 13 pages SPS Program



```
                    OREGON STATE UNIVERSITY E.E.DEPARTMENT
                               CORVALLIS, OREGON  USA

         THESIS TITLE

                         TRANSMISSION LINE TOWER LOCATION
                    ON NONFLAT TERRAIN BY DIGITAL COMPUTER METHODS

                                         BY

                                 SOMKIET PHALOPRAKARN

36002400050Z260004700054160005400001110005400000310013900010450001200K404900242
001600035001002600090002991700060 00J4003936000000005004900000012345678912345678
3600321005003600241005003600160005003600080005001500299000Z4900212
34567890J34567890JK4567890JKL567890JKLM67890JKLMN7890JKLMNO890JKLMNOP90JKLMNOPQZ
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14002630000P46001360110047001560130011002730000014900168012002680000014900168012
                        03600219005004400056002194900024044001680026315000262000
01010* LOCATING TRANSMISSION LINE BY DIGITAL COMPUTER  S PHALOPRAKARN           *
01020* FIRST JOB  READ DATA CARDS IN                                            *
01030JUMP  RNCDPUT+1                             90040200414360925000500Z
01040      SF   PUT+1                            90041400426320925000000Z
01050      SF   PUT+6                            90042600438320925500000Z
01060      SF   PUT+11                           90043800450320926000000Z
01070      SF   PUT+15                           90045000462320926400000Z
01080      SF   PUT+19                           90046200474320926800000Z
01090      SF   PUT+24                           90047400486320927300000Z
01100      SF   PUT+32                           90048600498320928100000Z
01110      SF   PUT+40                           90049800510320928900000Z
01120      SF   PUT+44                           90051000522320929300000Z
01130      SF   PUT+47                           90052200534320929600000Z
01140      TF   UTS50,PUT+5                      90053400546260909309254Z
01150      TF   UTS25,PUT+10                     90054600558260908309259Z
01160      TF   WH,PUT+14                        90055800570260912109263Z
01170      TF   WC,PUT+18                        90057000582260912509267Z
01180      TF   A,PUT+23                         90058200594260667009272Z
01190      TF   E,PUT+31                         90059400606260849509280Z
01200      TF   ALPHA,PUT+39                     90060600618260669409288Z
02010      TF   CG,PUT+43                        90061800630260833309292Z
02020      TF   POLEA,PUT+46                     90063000642260879009295Z
```
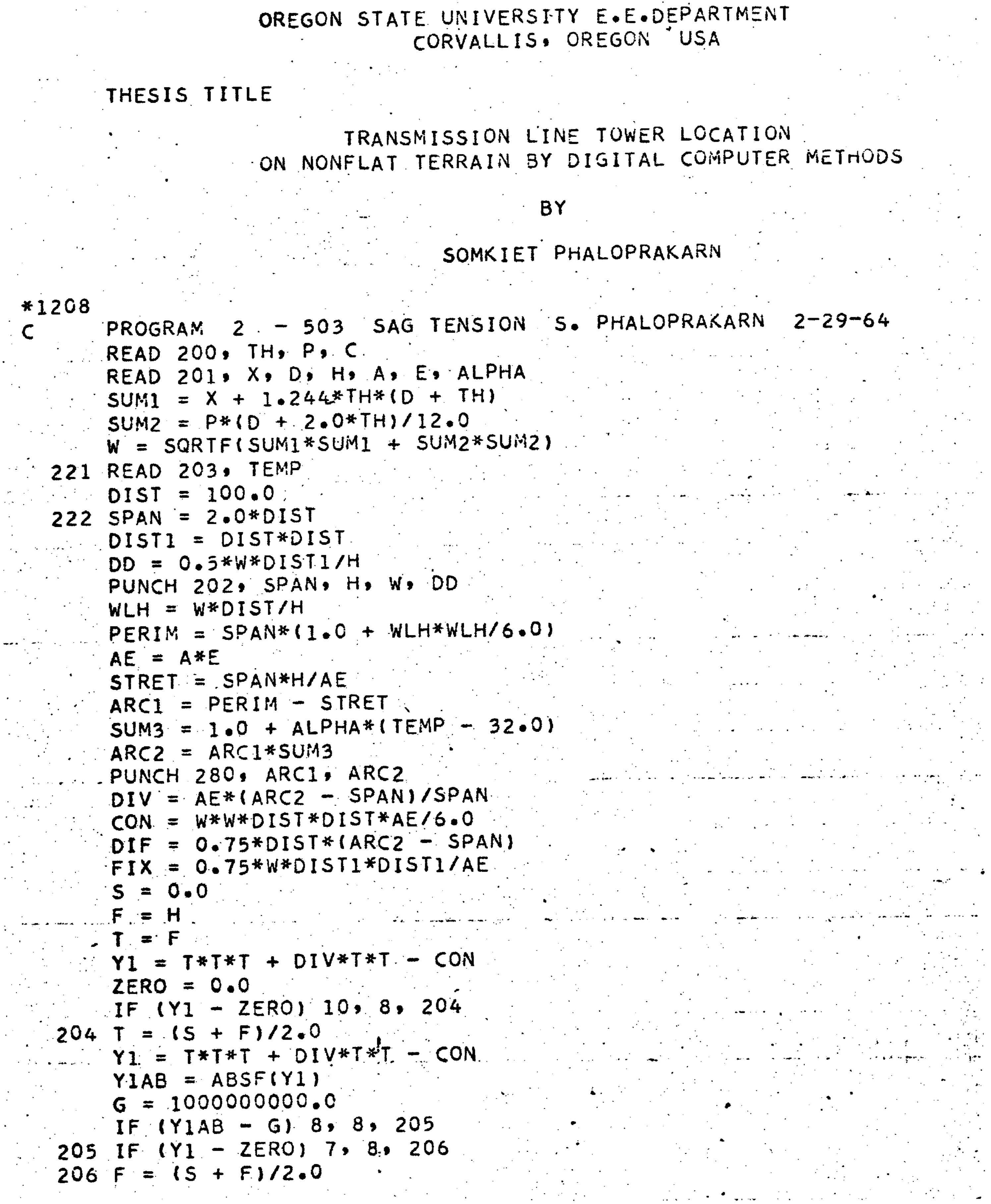

```
02120        AM   BOX,16,10                 90075000762110832400 0J6Z
02130        B    READ                      90076200774490067800000Z
05010START   TF   POL,POLEB                 90077400786260874608793Z
05020        TF   POLE,POLEA                90078600798260879608790Z
05030BEGIN   TF   PO,POLE                   90079800810260874308796Z
05035        A    PO,POL                    90081000822210874308746Z
05040        MM   PO,050,9                  90082200834130874300050Z
05050        SF   00095                     90083400846320009500000Z
05060        TF   POLE1,00099               90084600858260880100099Z
05070        S    POLE1,CG                  90085800870220880108333Z
05080        MM   POLE1,00008,7             90087000882130880100008Z
05090        TF   SHOP,00099                90088200894260888900099Z
05100        M    SHOP,UTS25                90089400906230888909088Z
05110        SF   00090                     90090600918320009000000Z
05120        TF   SHOP,00099                90091800930260888900099Z
05130        LD   00094,SHOP                90093000942280009408889Z
05140        D    00085,WH                  90094200954290008509121Z
05150        SF   00085                     90095400966320008500000Z
05160        TF   M,00094                   90096600978260870100094Z
05170        MM   M,75,10                   90097800990130870100 0P5Z
05180        TF   X,00097                   90099001002260913500097Z
05190MARK10MM     X,50,10                   90100201014130913500 0N0Z
05200        TF   SAVE,00097                90101401026260887900097Z
06010        MM   M,50,10                   90102601038130870100 0N0Z
06020        TF   LOAD,00097                90103801050260869100097Z
06030        TF   00079,ZERO10              90105001062260007909145Z
06040        LD   00094,LOAD                90106201074280009408691Z
06050        D    00085,X                   90107401086290008509135Z
06060        SF   00078                     90108601098320007800000Z
06070        TF   SAFE,00087                90109801110260886900087Z
06080        A    SAVE,SAFE                 90111001122210887908869Z
06090        MM   X,001,9                   90112201134130913500001Z
06100        TF   TEST,00096                90113401146260901900096Z
06110        TF   SUB,SAVE                  90114601158260885908879Z
06120        S    SUB,X                     90115801170220885909135Z
06130        CF   SUB                       90117001182330885900000Z
06140        C    SUB,TEST                  90118201194240885909019Z
06150        BN   PUNCH                     90119401206470123001300Z
06160        TF   X,SAVE                    90120601218260913508879Z
06170        B    MARK10                    90121801230490100200000Z
06180PUNCH   TR   OUT+1,BLANK-19            90123001242310933109412Z
06190        TF   OUT+10,SAVE               90124201254260934008879Z
06200        CF   OUT+1                     90125401266330933100000Z
07010        WNCDOUT+1                      90126601278380933100400Z
07020* PART ONE ENDED  ESTIMATED SPAN IS CALLED SAVE
K0010* PART TWO  LOCATE TOWER B
20020        SF   POINT-5                   90127801290320671500000Z
20030        SF   POINT-11                  90129001302320670900000Z
```

Sample Fortran Program for Sag-Tension Calculations



OREGON STATE UNIVERSITY E.E.DEPARTMENT
CORVALLIS, OREGON USA

THESIS TITLE

TRANSMISSION LINE TOWER LOCATION
ON NONFLAT TERRAIN BY DIGITAL COMPUTER METHODS

BY

SOMKIET PHALOPRAKARN

```
*1208
C     PROGRAM  2  - 503  SAG TENSION  S. PHALOPRAKARN  2-29-64
      READ 200, TH, P, C
      READ 201, X, D, H, A, E, ALPHA
      SUM1 = X + 1.244*TH*(D + TH)
      SUM2 = P*(D + 2.0*TH)/12.0
      W = SQRTF(SUM1*SUM1 + SUM2*SUM2)
  221 READ 203, TEMP
      DIST = 100.0
  222 SPAN = 2.0*DIST
      DIST1 = DIST*DIST
      DD = 0.5*W*DIST1/H
      PUNCH 202, SPAN, H, W, DD
      WLH = W*DIST/H
      PERIM = SPAN*(1.0 + WLH*WLH/6.0)
      AE = A*E
      STRET = SPAN*H/AE
      ARC1 = PERIM - STRET
      SUM3 = 1.0 + ALPHA*(TEMP - 32.0)
      ARC2 = ARC1*SUM3
      PUNCH 280, ARC1, ARC2
      DIV = AE*(ARC2 - SPAN)/SPAN
      CON = W*W*DIST*DIST*AE/6.0
      DIF = 0.75*DIST*(ARC2 - SPAN)
      FIX = 0.75*W*DIST1*DIST1/AE
      S = 0.0
      F = H
      T = F
      Y1 = T*T*T + DIV*T*T - CON
      ZERO = 0.0
      IF (Y1 - ZERO) 10, 8, 204
  204 T = (S + F)/2.0
      Y1 = T*T*T + DIV*T*T - CON
      Y1AB = ABSF(Y1)
      G = 1000000000.0
      IF (Y1AB - G) 8, 8, 205
  205 IF (Y1 - ZERO) 7, 8, 206
  206 F = (S + F)/2.0
```

```
      GO TO 204
    7 S = (S + F)/2.0
      GO TO 204
   10 T = (S + F)/2.0
      Y1 = T*T*T + DIV*T*T - CON
      Y1AB = ABSF(Y1)
      IF (Y1AB - G) 8, 8, 207
  207 IF (Y1 - ZERO) 13, 8, 208
  208 S = (S + F)/2.0
      GO TO 10
   13 F = (S + F)/2.0
      GO TO 10
    8 PUNCH 209, T, Y1
      S = 0.0
      F = 80.0
      T = F
      Y2 = T*T*T - DIF*T - FIX
      ZERO = 0.0
      IF (Y2 - ZERO) 211, 212, 210
  210 T = (S + F)/2.0
      Y2 = T*T*T - DIF*T - FIX
      Y2AB = ABSF(Y2)
      V = 0.01
      IF (Y2AB - V) 212, 212, 213
  213 IF (Y2 - ZERO) 214, 212, 215
  215 F = (S + F)/2.0
      GO TO 210
  214 S = (S + F)/2.0
      GO TO 210
  211 T = (S + F)/2.0
      Y2 = T*T*T - DIF*T - FIX
      Y2AB = ABSF(Y2)
      IF (Y2AB - V) 212, 212, 216
  216 IF (Y2 - ZERO) 218, 212, 217
  217 S = (S + F)/2.0
      GO TO 211
  218 F = (S + F)/2.0
      GO TO 211
  212 SAG = T
      PUNCH 219, SAG, Y2
      TEST = 600.0
      IF (DIST - TEST) 220, 221, 221
  220 DIST = DIST + 100.0
      GO TO 222
  200 FORMAT (3F4.2)
  201 FORMAT (F5.4, F6.4, F6.1, F6.4, F10.1, F8.7)
  202 FORMAT (4HSPAN, F8.2, 2X1HH, F7.1, 2X1HW, F12.8, 2X2HDD, F10.4)
  203 FORMAT (F5.2)
  209 FORMAT (2X1HT, E14.8, 3X2HY1, E14.8)
  219 FORMAT (3HSAG, E14.8, 3X2HY2, E14.8)
  280 FORMAT (4HARC1, F12.6, 3X4HARC2, F12.6)
      END
```