



THE APPLICATION OF THE DIGITAL TERRAIN
MODEL PRINCIPLE TO THE PROBLEM OF
HIGHWAY LOCATION

by

ROBERT ARTHUR LAFLAMME
A. B., College of the Holy Cross
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S. B., Massachusetts Institute of Technology
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Signature of Author.....
Department of Civil & Sanitary Engineering
Certified by.....
Thesis Supervisor
Accepted by.....
Chairman, Departmental Committee
on Graduate Students



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ROBERT ARTHUR LAFLAMME

SUBMITTED TO THE DEPARTMENT OF CIVIL AND SANITARY
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The Digital Terrain Model Principle is accepted as an accomplished fact. An investigation is conducted into the problem of applying the Principle to Highway Location. The particular form, shape and size of the Digital Terrain Model is discussed as is the coordinate system to be used. Various schemes for the distribution of points in the Model are given and the relative merits of each are pointed out. Computer programs to edit the terrain data are suggested. The various programs to relate the terrain data to a highway alignment are indicated and examples of programs presently in use are given. The problem of integrating these various programs into a unified system is investigated and specific recommendations are made. The programs necessary to solve the vertical geometry problems are indicated and examples are given. The programs required for computing earthwork quantities are divided into categories and the specifications for each group are given. The problem of utilizing the output from these various computer programs is defined and suggestions on methods and instruments to use are given. The present status of the Digital Terrain Model System for Highway Location is evaluated and some thoughts are expressed about its future.

Thesis Supervisor: C. L. Miller
Assistant Professor of Surveying

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INTRODUCTION

THE DIGITAL TERRAIN MODEL PRINCIPLE¹

The Digital Terrain Model (DTM) is a method for storing terrain data in a form which fully utilizes the capabilities of photogrammetry and electronic digital computers. The DTM principle was evolved to take advantage of photogrammetry as a data source and electronic computers as data reduction tools.

Prior to the use of photogrammetry as a source of topographic data, all terrain data was obtained from field surveys. Though this data was originally in numerical form (field notes), it was recorded in graphical form as contour maps, cross sections, or profiles. Since field surveys were a slow and expensive means of obtaining this data, the minimum amount of data necessary was taken. However, photogrammetry made it possible to obtain great quantities of data with comparatively little effort though this data was also recorded in graphical form as contour maps. The topographic data obtained through photogrammetry was stored as contour maps because the techniques and instruments available made this the most economical method. When cross sections or profiles were desired, they were obtained from these maps.

Prior to the use of electronic computers for processing the terrain data, the computations involving this data were performed using a

¹"The Theory and Application of the Digital Terrain Model," C. L. Miller, M.S. Thesis, MIT, June, 1958, unpublished.

combination of analog, graphical and numerical methods. An example of the analog method is the calculation of a cross sectional area using a planimeter. An example of a graphical method is a cross section in which the intersection of a line and the terrain is found by drawing the line on the cross section. The numerical methods used included the calculations of volumes from cross sectional areas using the average end area or prismoidal formula. When electronic computers became available, this process was adapted to machine computations. This meant that the cross sections had to be converted to numerical form before they could be used by the computer. It was evident that this adaptation of old techniques to entirely new tools yielded a system which did not take full advantage of the characteristics and capabilities of either photogrammetry or computers. The DTM was developed to overcome this disadvantage.

Since the DTM was developed for the specific purpose of storing terrain data obtained from photogrammetry in a form easily usable by a computer, three main characteristics had to be incorporated into the principle: (1) It must have the capability of storing data for an area, as opposed to a line, (2) The data must be in numerical form, (3) The data must be stored on computer input material such as punched cards, punched paper tape, or magnetic tape.

Briefly, the DTM is a method of statistically representing terrain by recording the coordinates of many points over the area of interest

and storing this information directly on some form of computer input material. There are three portions of the above description worthy of further description: (1) The coordinate system used, (2) The selection of points, and (3) The procurement of the data through photogrammetry.

COORDINATE SYSTEM

The DTM principle specifies no particular coordinate system and the only requirement is that a Cartesian system be used. However, as a matter of convenience, a "right-handed" coordinate system is usually specified though a "left-handed" system can be accommodated.

In practice, a convenient data coordinate system is usually established and is referenced to the master coordinate system. Figure 1, from the MIT DTM System Manual, shows a typical data coordinate system, labelled "DTM Coordinate Axes." If the area of interest is rectangular, the x-axis is established parallel to the long dimension of the band. If the area is a square, the x-axis can be parallel to any side. The origin is usually located so that the band of interest lies within the first quadrant in order to eliminate the need for negative coordinates.

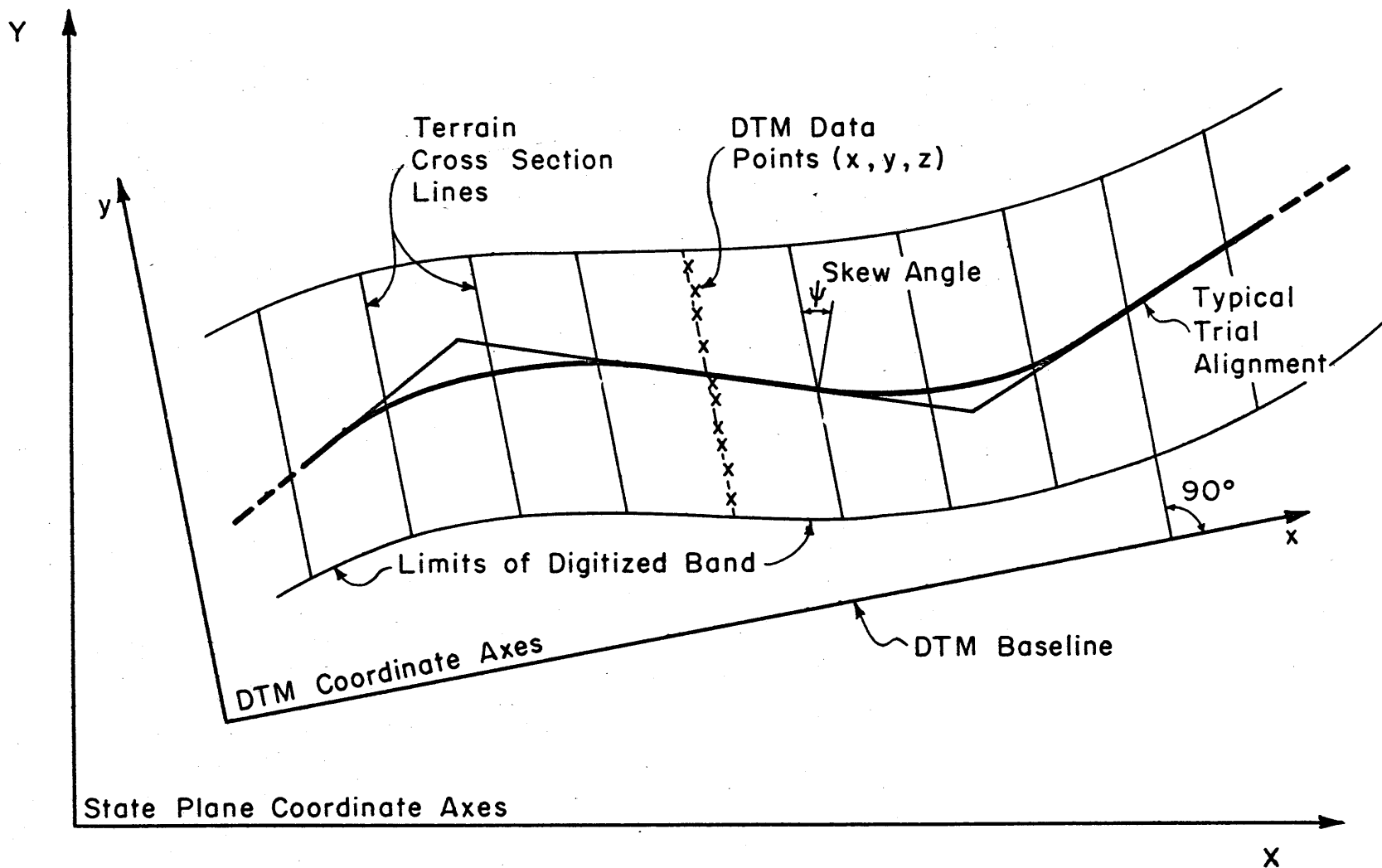
The question sometimes arises as to why a data coordinate system is used. This can be answered by stating that there is no ad-

vantage in using the master coordinate system and that the orientation of the master system may not be that desired. The reasons why a particular orientation of the data coordinate system is desirable will become clear in the following sections.

SELECTION OF POINTS

In the definition of the DTM principle, there is nothing said about the distribution of points over the area of interest. In fact, the only restriction on the arrangement of points is that they be recorded in a systematic manner so that they may be easily handled by the computer. If the points were recorded in a random manner, the entire set of points, or some portion of it, would have to be searched whenever a particular point was desired.

There are various ways in which the points may be arranged so that they meet the restriction. One such scheme is to record the elevations of points on a fixed x-y grid. This is called the "rigid-grid" system and in the simplest form requires recording only one coordinate, z, for any point once the grid orientation, origin and interval are known. The great advantages of this system are the minimum amount of data required for any point and the high degree to which data procurement can be automated. The disadvantages are lack of flexibility and the necessity of taking a higher density of points

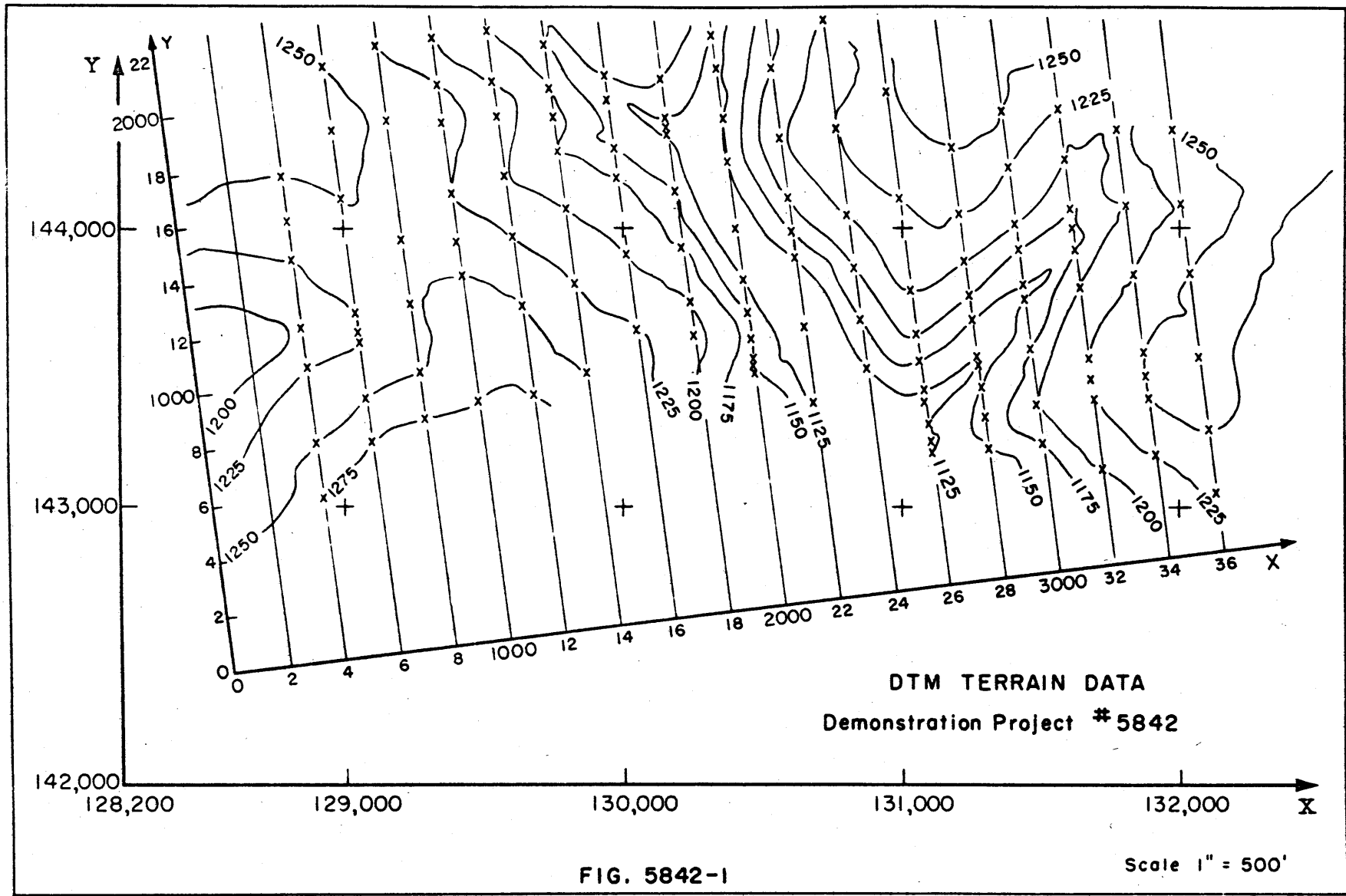


DIGITAL TERRAIN MODEL SYSTEM
 PRINCIPAL COMPONENTS AND NOMENCLATURE

for any given accuracy of representation. ("Higher density" refers to other schemes and will be explained in the following paragraphs.)

Another method of arranging the points is to take them along lines parallel to the y-axis. Since these lines have a constant x-coordinate, the x-value must be recorded only once for each line. Along a given line (scan line), the points may be taken at constant y increments, constant z increments or variable x and y increments. If either a constant y or constant z increment is used, less data will be required for each line but there will be less flexibility and more points will be required. If a variable y and z are used, more data will be required for each point but fewer points will be taken since they may be taken at breaks in the terrain. Figure 2, from the MIT DTM Manual, illustrates points taken at uneven y increments on scan lines. As mentioned previously, the less flexible (more rigid) a scheme is, the greater the number of points required compared to a fully flexible system. This also applies to taking the scan lines at variable x increments as opposed to constant x increments.

Another scheme, one that is considerably different from those mentioned above, is to record the x and y coordinates of points along lines of constant z (contour lines). The great advantage of this scheme is that the data procurement would be relatively simple using any one of the x-y recorders commercially available. Though this method is



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Figure 2

not presently being used, it holds considerable promise for the future.

Of the schemes mentioned above, the most flexible one (variable x, variable y, variable z) is the one that is presently being used. This does not imply that it is the best method, but rather, indicates that insufficient time has been available to investigate the other schemes.

DATA PROCUREMENT

As stated previously, the data for the DTM is normally taken using photogrammetric methods. The two primary sources of the data are the photogrammetric contour map and the photogrammetric model itself. In either case the use of special instrumentation can play an important part.

Photogrammetric maps at various scales are generally available and in extensive use in present practice. The DTM sections can be taken from contour maps with very little equipment since all that is needed is a scale to measure the distances. The data is then tabulated and later translated into computer input material. This means that anyone with a contour map can start taking DTM data immediately. It is obvious, however, that the process of obtaining the great quantities of data necessary for the DTM is tedious and

that some means of improving this process is very desirable. There are various approaches to the problem but the desired instrumentation must essentially be a unit that will measure the y-coordinates of points and punch or print out the y and z values. Though direct punching is very desirable, a direct print-out is a great advantage over using an engineer's scale, manually recording the data, since key-punching the data from tabulations is a relatively simple and fast process. When instrumentation which automatically puts the data on computer input material is used, the problem of data procurement is even further reduced. One further point should be mentioned. As the method of obtaining the data becomes more and more automatic, the opportunities for human error become less. This is a very significant advantage where great quantities of data are concerned.

The second source of DTM data, the stereo model, appears to be the logical place to obtain the data since it is also the source of photogrammetric contour maps. However, there are certain factors which make it unfeasible in many instances to obtain the data directly from the stereoplotter. The first important factor is that whereas contour maps are generally available, stereoplotters are not. This does not mean that someone who uses maps obtained from a mapping firm cannot also obtain DTM data from their stereoplotters. On the contrary, some of the mapping firms are already furnishing DTM data

on computer input material when so requested. On the other hand, it must also be remembered that at present this is the exception and also that the availability of DTM data does not eliminate the need for maps. The second factor which must be considered when the procurement of data directly from the stereomodel is being weighed, is that the commonly used stereoplotters are designed for producing contour maps, not cross sections. They are constructed to graphically plot the data obtained from the stereomodel rather than output the information in numerical form. Therefore, in order to obtain cross-sectional data with any efficiency from such a plotter, special instrumentation must be used. Since the plotters have a means of recording elevations, the minimum additional instrumentation is a device which will measure the y-coordinate. Again, the most desirable device is one which will automatically punch out the x, y and z coordinates of points. The important point to remember is that it is not possible to obtain DTM data with only an engineer's scale and a pencil and paper.

APPLICATIONS

The DTM, as described above, is a general principle and is not directly tied to any particular application. The DTM principle

can be used for any problem where numerical calculations involving terrain data are involved. This is particularly true when an area of interest is concerned, such as the area in which an airport is to be constructed.

The DTM can be very efficiently used in the problem of highway location since the same set of terrain data can be used to evaluate the earthwork quantities for any number of trial lines. The problem of locating a dam is similar to that of locating a highway though different criteria are used. The DTM can also be applied to this problem. Calculating the volumes of stock piles and borrow pits is another type of problem where the DTM is clearly applicable. Into this category of problems falls that of determining volumes for open-pit mining.

The application of the DTM Principle to the problem of Highway Location is of great interest and importance, particularly because of the impetus given to highway construction by the 1959 Federal Bill creating the Interstate system of roads. This thesis attempts to analyze the steps involved in applying the Digital Terrain Model Principle to the problem of highway location using as examples throughout the work done at the MIT Photogrammetry Laboratory.

THE DIGITAL TERRAIN MODEL FOR HIGHWAY LOCATION

Though the Digital Terrain Model is a method of storing terrain data, the Digital Terrain Model System is a combination of the DTM and a group of computer programs to process the DTM data. The DTM principle has been explained in the preceding pages but no mention was made of any computer programs. Therefore, this section will assume the DTM principle and show what must be done to apply it to a particular problem, highway location. The first portion will show what particular form the DTM must take, what coordinates are used, and how the data is procured. Various computer programs to edit and process the terrain data will be indicated and an example will be given. Succeeding sections will discuss the various computer programs necessary and the problems involved in utilizing the output from the various programs.

THE DIGITAL TERRAIN MODEL

The problem of highway location is normally concerned with selecting one or more alignments to connect two given points. The problem will vary from that of locating a road to connect two isolated towns in undeveloped areas to that of revising a portion of some existing alignment. Regardless of the particular problem, one cri-

terion for selecting one alignment over another is the earthwork cost. If the area is uninhabited and the land owned by the agency locating the road, earthwork will be the primary cost. In the case of heavily populated areas, other factors, such as existing structures, will control. However, earthwork will still be computed and in no case will be neglected.

Since the area of interest is usually rectangular, the DTM is also usually rectangular. The band of interest will normally narrow near the ends and may widen in the center portion. Certain parts of it may be eliminated, e. g., it may be decided that under no condition will the road go through a particular cemetery, and there may be regions within the band of interest where no data need be taken. By judiciously examining the area involved, it is often possible to eliminate many regions. Eliminating these areas can greatly reduce the amount of unnecessary data that would otherwise be taken.

The actual size of the band of interest will vary greatly with the phase of the location study. In a reconnaissance study, the band of interest may be two miles wide with points 100 feet apart. On the other hand, if the final location of a line is desired, the band of interest may be only 1000 feet wide with points averaging 10 to 15 feet apart. Since the actual width of the band and the density of points do not affect the principles involved, no particular

size will be assumed.

For any given project, some direction is normally selected as being that of increasing stationing. The Baseline will therefore be selected so that it is parallel to the long dimension of the band and so that the Baseline x coordinate increases in the same direction as the center line station. It will also be placed in such a position that all y-coordinates will be positive to eliminate the need for negative coordinates. This, therefore, defines the data coordinate system. Figure 2 illustrates the positioning of a DTM Baseline.

Up to this point it has been assumed that the master coordinate system would be a State Plane Coordinate System. Though this will normally be the case, under certain conditions, it may be more practical to use some other coordinate system. Since the choice of master coordinates system has no effect on the DTM principle and since State Plane coordinates are commonly used as master coordinates, the ensuing discussion assumes that the master system is State Plane Coordinates.

Now that the coordinate systems have been specified, it is well to determine which configuration of points will be used. As mentioned previously, any arrangement from a rigid grid to a random distribution may be used. For the particular case of highway loca-

tion, we will use a system which is similar to the normal practice, i.e., points will be taken at irregular y intervals along lines of constant x value. (See Figure 2) The DTM cross sections will, therefore, be similar to right-angle cross sections; points will be taken at breaks in the terrain along sections and extra sections will be added wherever there is an abrupt change in the terrain between sections. In doing this, the accuracy of the representation of the terrain will be as good as that obtained using normal cross sections. The interval between sections will usually be constant, ranging from 50 feet to 1000 feet depending on the terrain and the accuracy desired, and extra sections will be added wherever necessary.

Since the source of this DTM data has not yet been decided upon, this will now be done. Two sources will be considered: photogrammetric contour maps and the photogrammetric stereo-model. Though in some cases data from field surveys may be used with the DTM, this is an unusual case and will not be considered.

Photogrammetric contour maps will be assumed to be the primary source of DTM data since they are generally available and no special instrumentation is required. The stereoplotter will be considered the secondary source, not because it is less suitable, but rather because it, and the associated instrumentation, is less generally available. The maps or plotter can be used interchange-

ably in the system, and on occasion, the terrain data may come from a combination of both sources. Therefore, the choice of data source does not affect the DTM System.

The process of obtaining DTM data is usually slow and correspondingly expensive. For this reason, some mechanical or electronic aids to data procurement are desirable. Before specifying what these aids should be, let us examine the steps involved in manually obtaining the data from a map. Given the map, the Baseline must be drawn on it. Next, the cross section lines are drawn perpendicular to the Baseline. Then we are ready to take data. The x value for a cross section is written down and an engineer's scale is used to measure the distance to the first data point. This is recorded. The contour crossing or interpolated elevation at that point is then recorded. This process is repeated until all the data for a section has been recorded. Then a new x value is recorded and the entire process repeated. Since we are assuming the primary storage medium to be IBM cards, the cards must now be keypunched from the data. The cards must then be verified to guard against keypunch errors. We now have our Digital Terrain Model.

The ideal process would merely require the operator to position an index mark over a point and push a button, punching the co-

ordinates of the point into a card. Such a system would be very desirable, but also very expensive. By examining the manual process, we can arrive at a solution in between the manual and fully automatic processes that will be adequate and relatively inexpensive.

The actual punching of the cards seems to be a process that can easily be automated, yet it requires that a keypunch be available and that electronic readout circuitry be also available to drive the punch. On the other hand, an experienced keypunch operator can punch great quantities of data from tabulated sheets in a very short time. Since anyone having a card input computer would also have keypunches and keypunch operators available, obtaining the data in neatly tabulated form would not be as inefficient as it first seemed.

Recording the x coordinate of a section need be done only once per section. Therefore, if this step remains manual or semi-manual we have not lost too much efficiency.

The scaling of the y-coordinate and the recording of the y and z coordinates constitute the most tedious portion of the data procurement phase. The process is tiring and monotonous and is, therefore, a primary source of error. The basic instrumentation to perform these operations should allow the operator to place the index mark over a point and press a button to print out both the y and z coordinates. The y coordinate can be measured by any of a number of methods

but the z, or elevation, must be at least partially determined by the operator since it is obtained from contour lines. One method of doing this is to take the data points at contour crossings and use a counter to record the contour elevation. The counter could be augmented by the contour interval, remain the same, or be decreased by the contour interval, depending on the change from the previous point. The operator would then have to push two buttons, one to indicate the change in elevation (z), and one to readout the y and z. Such a system, with a few additional refinements has been designed and built by the staff of the MIT Photogrammetry Laboratory and offers great promise as a low cost device for obtaining DTM data.

Once the data has been recorded, keypunched and verified, there are a certain number of operations that may be performed on it. The data can be checked to insure that it meets the specifications, e. g., that the points were taken in order of increasing y coordinates. Another operation that may be performed is to alter the card format, e. g., change the format from 4 points per card to 7 points per card. Still another operation would be to correct an intentional violation of a specification. An example of this would be to record every other section in order of decreasing y coordinates. The advantages of doing this are fairly obvious since the data procurement would become a "back and forth" process

eliminating the need to return to the Baseline before taking the next section. This is particularly useful with automatic readout systems.

Since the data is on punched cards, it is only logical to use the computer to perform the above mentioned operations. The first DTM computer program to operate in this manner is the Terrain Data Edit program, TD-1; "TD" stands for Terrain Data and will be used to identify all programs which fall into this category. It is expected that in time, a number of computer programs will be written which will perform all the operations mentioned above and some which have not yet even been contemplated.

For the series of programs developed at MIT, the terrain data is stored in the so-called "four per card" format, i. e., each card has the x value of the section and four y-z combinations for four points. Figure 3 shows the card format used for terrain data in the MIT series of programs. A section will, therefore, consist of as many cards as are necessary to contain all the points. The TD-1 program, written by R. A. Baust of the MIT Photogrammetry Laboratory staff, checks the terrain data to ensure that the cross sections are in order of increasing x, the points are in order of increasing y, the x value of points for a cross section agree, the cards are punched in the proper format. When a violation of the

DTM TERRAIN DATA - IBM CARD TD FORMAT A
(Standard Format for DTM Programs)

Beginning-of-Line Card (one per terrain cross section)

cc

1-5	NNNNN	Identification Number
6-11	xxxxx.x	DTM x coordinate of the cross section
12-80		Blank

Terrain Data Cards (up to four points per card)

cc

1-5	NNNNN	Identification Number	
6-11	xxxxx.x	x coordinate	
12		11 punch (identifies card as terrain data)	
13		Blank (or 11 or 12 punch)	
14-18	yyyy.y	y (offset)	
19		Blank	First Point
20-24	zzzz.z	z (elevation)	
25-29		Blank	
30		Blank (or 11 or 12 punch)	
31-35	yyyy.y	y	
36		Blank	Second Point
37-41	zzzz.z	z	
42-46		Blank	
47		Blank (or 11 or 12 punch)	
48-52	yyyy.y	y	
53		Blank	Third Point
54-58	zzzz.z	z	
59-63		Blank	
64		Blank (or 11 or 12 punch)	
65-69	yyyy.y	y	
70		Blank	Fourth Point
71-75	zzzz.z	z	
76-80		Blank	

Error Designation - 12 punch in cc 13, 30, 47, 64 signifies that the previous terrain point is in error and is to be ignored by computer.

Partial Card (less than 4 points on a card) - 11 punch in cc 13, 30, 47, 64 signifies that there is no more significant data on the remainder of the card.

Punch Requirement - card columns 6-11, 14-18, 20-24, 31-35, 37-41, 48-52, 54-58, 65-69, and 71-75 must all be punched with a number. Use a zero if the number is not significant. Example, a z of 282' should be punched as 02820.



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specifications is detected, an error card indicating the type and location of the error is punched. The engineer then uses this information to correct the error. Once the errors have been corrected, the data is again processed using TD-1 to insure that no errors were missed and that the corrections were indeed correct. When the entire deck of DTM data has been processed by TD-1 without detecting any errors, it is then ready for use.

The use of the TD-1 program is explained in the Digital Terrain Model System Manual. This manual is divided into three parts: Part I, Engineering Instructions; Part II, Operating Instructions; Part III, Program Analysis. Part I is intended for the engineer and gives him the information he needs to use the program. It contains no information concerning the actual computer operation nor concerning the program itself since he need not know this in order to use the program. Part II contains the information necessary for the machine operator, the person who pushes the buttons and actually operates the machine. This part of the manual contains no engineering instructions but essentially tells the operator what buttons to push. Part III contains the information of interest to the programmer or applications engineer who wishes to understand or modify the program. The manual is divided into three parts so that the engineer will not have to wade through much superfluous information to obtain that which he desires. In a like manner,

the operator will not have to wade through the engineering instructions or the program write-up, nor will the programmer have to go through the engineering instructions. Since the manual has been written in "cook book" fashion, the engineer, operator, or the programmer, does not have to waste a great deal of time reading before he obtains the information he desires.

Appendix A contains the engineering instructions, operating instructions and program analysis of the TD-1 program. This write-up clearly shows the form of the DTM Manual and the manner in which it is written.

The importance of this manual cannot be understated. Without it, the programs are useful to no one but the authors. Therefore, until the instructions for its use are available in a form that makes them easy to understand, the program is practically valueless. The manual is therefore equally as important as the programs and the necessary effort should be expended to make it useful.

THE HORIZONTAL GEOMETRY PROBLEM

Horizontal geometry problems are those concerned with the geometrical relationships in the x-y plane. This includes the basic problem of relating the data coordinate system to an alignment and also such problems as computing the stationing for points along any given

alignment. As will be seen, certain problems which do not properly belong to this category are included in it for the sake of convenience.

The basic problem in using the DTM for highway location is that of relating a horizontal alignment, defined in the master (State Plane) coordinate system to the terrain data defined in the data coordinate system. The data coordinate system is related to the master system by measuring, or computing, the State Plane coordinates of the Baseline (x axis) origin and measuring or computing its azimuth. This is the information necessary to specify the rotation and translation of one system relative to the other. The problem therefore reduces to that of determining the intersection of each cross section and the alignment.

The horizontal alignment of a highway is normally composed of tangents, circular curves, and sometimes spirals. This alignment must be mathematically defined so that the intersections may be computed. The tangents may be defined by giving the State Plane coordinates of their intersections (P.I.'s). The circular curves joining the tangents are normally defined in one of two ways: by giving the radius of curvature or by giving the degree of curvature. Either of these two methods of defining a circular curve is acceptable. The spirals are normally used to join the circular curves to the tangents; in the normal case, there would

be a spiral at each end of a circular curve. The spirals are normally defined by giving their lengths. An alignment may therefore be fully defined by giving the State Plane coordinates of the P.I.'s, the radii of the circular curves, and the lengths of the spirals. In order to obtain the proper stationing along the alignment, the station of one point, e.g., the origin, must be given.

Before the intersections of cross sections and the alignment can be computed, certain other parameters of the alignment must be known. The stations of the T.S., S.C., C.S., S.T., and the azimuths of the tangents must all be known before any intersection may be computed. This additional data can all be computed from the data specifying the alignment. These computations can be performed by the computer and since the answers are also of interest to the engineer, they can be punched out. All this data could be input to the computer, but this would require the engineer to perform calculations which can be performed much more efficiently by the machine.

Once the alignment is fully defined, the intersection of the cross sections and the alignment can be computed. This intersection point is then defined by the center line stationing, the baseline y coordinate and also the skew angle, the angle between the cross

section line and the normal to the alignment at that point. These four parameters are referred to as s , y , and ψ , respectively.

The problem of computing the intersection can be divided into three parts: (1) Computing the intersection of a cross section and a tangent, (2) Computing the intersection of a cross section and a circular curve, and (3) Computing the intersection of a cross section and a spiral. Though the first two are straight forward and can be computed directly, the problem of determining the intersection of a cross section and a spiral is not as simple. The problem reduces to that of solving for the intersection of a straight line (a cross section line) and a third degree curve (approximating a spiral). Though a direct solution to this problem is possible, it appears more feasible to solve by the method of successive approximations.

One or more computer programs are required to solve the problems stated above. These programs and all other programs for this system must meet a certain set of criteria if they are to be a true system, rather than just a series of computer programs. The main criterion that the programs must meet is that they be compatible. They must be developed and written bearing in mind that they are part of an overall system. The IBM 650 computer, for which the first series of programs were written, requires that

a control panel be used in the input-output unit to regulate card formats. Rather than have a separate control panel for each program, as may easily occur, all, or as many as possible, of the programs should be written so that they use the same control panel. Since the output of some programs will serve as input to others, this should be kept in mind so that the cards punched as output may be used as input without any intermediate processing. The precision of all the programs must be geared to the same level so that one program does not compute centerline stationing to the nearest tenth of a foot while the program which will use this data carries all computations to the nearest thousandth of a foot. Though it may not be feasible to keep the scaling in all programs exactly alike, some effort at uniformity must be made. The procedure for using the programs must be as uniform as possible so that an entirely different operating procedure is not required for each program. The writeups for all the programs must follow the same general outline so that it will be simple for the engineer or operator to obtain the desired information. By keeping all these things in mind it becomes a simple matter to develop an integrated system of programs, each of which can be easily used once the system is known.

Now that the criteria all computer programs must meet have been stated, it must be decided what computer programs are required to solve the horizontal geometry problem. The first pro-

gram needed is one which can be called the Basic Horizontal Alignment Program. This program should solve the basic problem of relating the cross sections to a particular alignment.

Input data to this program will fall into two categories, the terrain data information and the horizontal alignment information. The terrain data information would be a combination of the DTM cross sections and the data relating the data coordinate system to the master system. This data would be: X_0 and Y_0 , the State Plane coordinates of the Baseline origin, and θ , the azimuth of the Baseline. The alignment data, for an alignment composed of tangents and circular curves with symmetrical spirals, would be as follows: X_1 , Y_1 , the State Plane Coordinates of the alignment origin; X_i , Y_i , the State Plane Coordinates of each of the P.I.'s; X_n , Y_n , the State Plane Coordinates of the alignment terminus; R_i , L_i , the radii of the circular curves and the lengths of spirals (if a curve has no spirals $L_s = 0$); and S_0 , the centerline stationing at the origin of the alignment.

The computations would also fall into two categories: the computations to determine the various parameters of alignment geometry such as stationing and azimuths, and the computations for each cross section.

The input data defines the alignment with the minimum informa-

tion necessary. There still remain many parameters which the engineer needs and which he would normally have to compute by hand. Since the necessary information is available to the computer, various parameters are computed, saved for use in the cross section computations, and also punched out so that they are available to the engineer. This information consists of the azimuths of the tangents, the stationing of the T.S., S.C., C.S., and S.T. for each curve, the distance from the P.I. to the T.S. and S.T. of each curve, the intersection angles of the tangents, and various other constants for each curve.

Each cross section must be related to the alignment by computing the baseline y-coordinate of the alignment intersection, the centerline stationing at the intersection, and the angle between the cross section and the alignment or the tangent to the alignment at that point. This set of data must be computed for each cross section and this is done once the alignment parameters have been computed. One additional piece of data is computed for each section, the terrain elevation at the centerline. This is easily obtained by linear interpolation and provides the engineer with a centerline profile he can use to select the vertical alignment.

The above program, in addition to providing data from which a profile can be drawn, also provides information for plotting a



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plan view of the alignment relative to the baseline. The baseline will serve as the reference for plotting the outputs of nearly all the programs in the system, and will therefore provide a common denominator for all these outputs.

Since it is often desirable to plot right-of-way limits and sometimes shoulder lines, the basic program can be modified to compute, in addition to the data for the intersection of each cross section and the alignment, the y coordinate of the intersection of the cross section and each of two offset lines. If the offset distance correspond to the right-of-way distance, the output could be used to plot this line. If the offset distance corresponded to the distance from the centerline to the shoulder point, this shoulder line can be plotted. If, in addition to computing the y-coordinates of the intersection of the cross section and the offset lines, the program also computed the terrain elevation at this intersection, this data would provide the engineer with information about the slope of the terrain in a direction perpendicular to the alignment at each section. Such information would be useful in selecting the grade line.

Another version of the basic program would be one which would compute only the alignment geometry. This would not be a true DTM program since no cross sections would be involved, but it would provide the engineer with a general purpose program he could use

to check the alignment before using the basic horizontal alignment program.

Still another modification of the basic program can be used to generate data for plotting purposes without using the terrain data deck. Such a program would compute the intersection of the alignment and scan lines at constant intervals along the Baseline. Instead of taking the x value from cross sections and using this value to compute the intersections, the program would take an initial value of x, determine the intersection of a scan line having that x value with the alignment, increment the x value by a given interval, determine the intersection, and keep repeating this process until the terminus was reached. The alignment could then be plotted with reference to the Baseline. There would be two main advantages to such a program: (1) The terrain data deck would not be used, and (2) The interval used to increment x could be given any value, independent of the cross section spacing. The main drawback would, of course, be the lack of a profile. However, since the program would be used only to generate data for plotting purposes, this drawback would be of no consequence.

There are many variations of the basic program possible and each would have its own particular application. As the system becomes more commonly used and experience using it is gained, new

applications and problems are discovered. For this reason, the number and type of programs desirable will not remain constant but will grow with the system. The programs and variations indicated above are those which appear desirable from a theoretical standpoint and are basic to the system.

The first set of horizontal alignment programs for the DTM were developed at the MIT Photogrammetry Laboratory. They consist of a basic horizontal alignment program, a variation to include offset lines, and a variation to compute the geometry only. In addition to these three, a straight line interpolation routine was written to obtain profile elevations on even stations.

The DTM Basic Horizontal alignment program, called HA-1, is very similar to the ideal program already described. The main difference is that the HA-1 program uses a horizontal alignment composed only of tangents and circular curves; no spirals are allowed. This is not as great a drawback as it would first appear since in location work the inaccuracies introduced by approximating spirals by combinations of circular curves are not significant. Therefore, for purposes of location study, where alternate lines are being compared, there is no great advantage in using spirals.

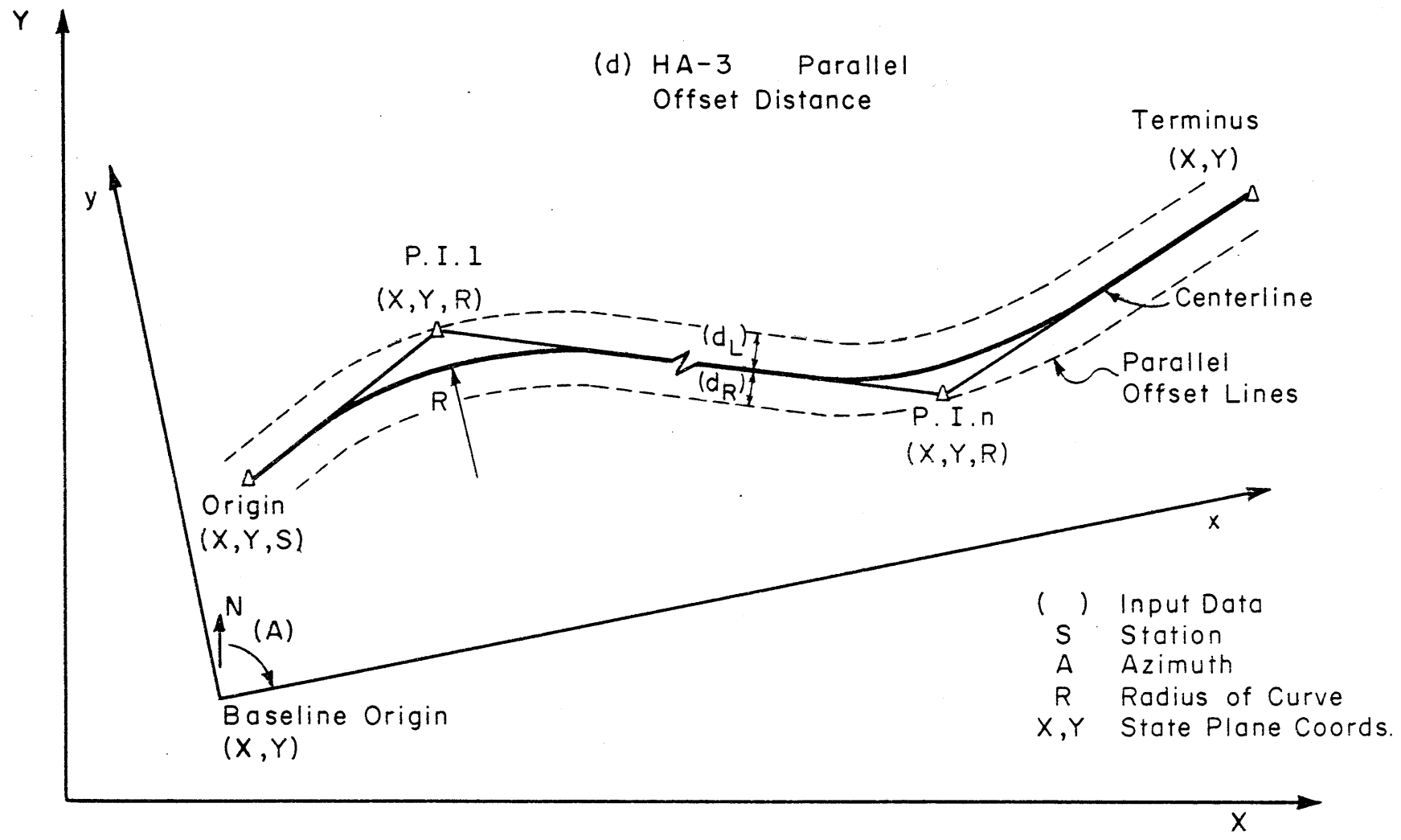
The input to this program is the terrain data deck; the Baseline Data Card containing X_0 , Y_0 (The State Plane Coordinates

of the Baseline origin) and θ (the azimuth of the Baseline); the horizontal alignment definition cards containing X_i , Y_i (The State Plane Coordinates of the alignment origin, terminus and each P.I.), and R_i (the radius of each circular curve). Figure 4 illustrates the input data needed.

The program computes the geometry of the alignment and punches out the centerline station of the P.C.'s and P.T.'s, the azimuths of the tangents, the intersection angles and the tangent distances. For each cross section, the program computes and punches out the centerline station, S_x , the Baseline y-coordinate of the intersection of the alignment and the section, and the angle between the section and a normal to the alignment at this point. The program also interpolates for and punches out the terrain elevation at the centerline. Figure 5 illustrates the output of the program.

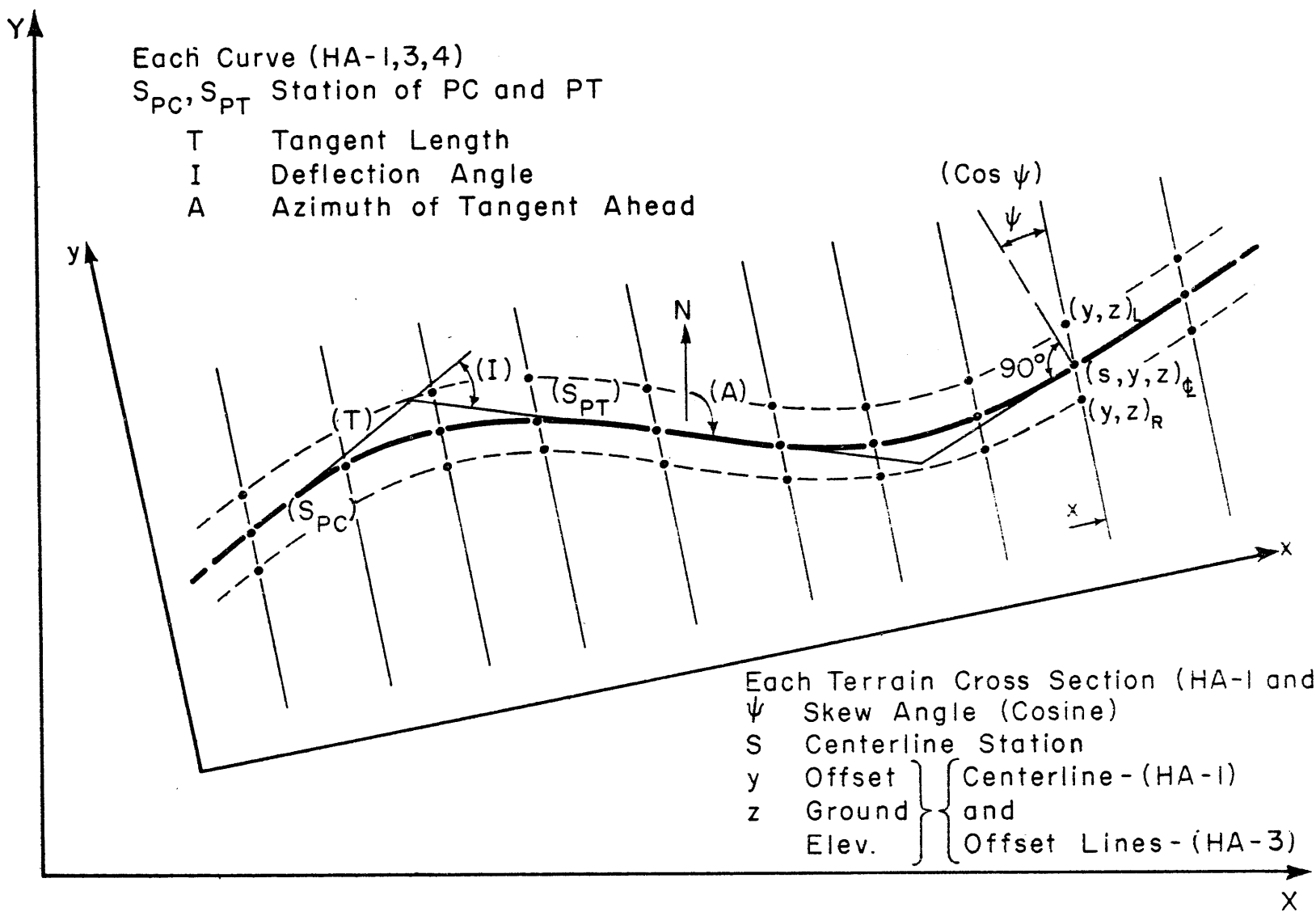
This program serves as the basic horizontal alignment program and except for its inability to handle spirals, fulfills all the requirements of such a program. It is expected that with time, this program will be revised to include spirals.

In addition to the basic program, two variations of it have also been written. These two variations correspond to the two mentioned in the previous discussion. The program to compute only the geometry of the alignment has been written as



DTM HORIZONTAL ALIGNMENT PROGRAMS HA-1,3,4
 INPUT DATA TO DEFINE EACH TRIAL ALIGNMENT
 Fig. HA-1

Figure 4



Each Curve (HA-1,3,4)
 S_{PC}, S_{PT} Station of PC and PT
 T Tangent Length
 I Deflection Angle
 A Azimuth of Tangent Ahead

Each Terrain Cross Section (HA-1 and HA-3)
 ψ Skew Angle (Cosine)
 S Centerline Station
 y Offset } { Centerline - (HA-1)
 z Ground } and
 Elev. } { Offset Lines - (HA-3)

DTM HORIZONTAL ALIGNMENT PROGRAMS HA-1,3,4
 OUTPUT DATA FOR EACH CURVE AND CROSS SECTION
 Fig. HA-2

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has the variation to include offset lines. Since these two variations are nearly identical with the programs described previously, they will not be gone into. The input and output of these two programs is shown on Figures 4 and 5.

Appendix B contains the program analysis for HA-1, HA-2, HA-3 and HA-4 and in addition to illustrating the functions performed by the programs, shows their complexity.

The problem of selecting the horizontal alignment has intrigued engineers for many years. In the past, and presently, the horizontal alignment of a road is selected by an engineer using maps, profiles, photographs and various other aids. Since the advent of electronic computers, much interest has been aroused in using the computer to select the best, or "optimum", line. Though many factors enter into the location problem, earthwork in many instances is the principal or at least an important factor. For this reason, the problem of selecting the best line on the basis of earthwork has been studied. Since there is only one criterion, the problem appears relatively simple. However, no satisfactory solution has yet been obtained. The DTM Principle presents an ideal method of storing the terrain information and, using a high speed computer, the problem may not be too far from a solution. The research in this field is continuing and before too many years, a solution should be forthcoming.

VERTICAL GEOMETRY PROBLEM

Once a trial alignment has been related to the cross sections and fully defined in the horizontal plane, there still remains the problem of selecting a grade line, or vertical alignment. The horizontal alignment program computed for each cross section the centerline station, S ; the baseline y offset, y ; for the intersection of the alignment and the section. One more factor remains to be computed before the earthwork volumes can be calculated, this is the profile elevation for each cross section, Z_p . The computation of this elevation is the vertical alignment problem.

The vertical alignment program must compute Z_p and add it to the output of the horizontal alignment program. The input to the program will therefore consist of the data defining the profile and also the output of the horizontal alignment program. The output will consist of the value Z_p added to the input data for each cross section. As mentioned previously, this vertical alignment program is one of a series, and as such, must be an integrated portion of the system. It must accept as input the output from the previous program and be consistent with it as much as possible. It is possible to compute Z_p by conventional methods, or using a program which is not integrated into the system. However, if this is done, the systems approach to the problem is lost and many sources of error are introduced.

The basic vertical alignment program must take as input, data defining the vertical alignment and compute the elevation Z_p for each cross section. If the vertical alignment is composed of grades and parabolic curves, it may be defined in a number of ways. Probably the simplest way, and the one that will be used, is to define the profile by giving the station and elevation of the origin, terminus, and V.P.I.'s and the lengths of the parabolic curves. The other parameters, such as the grades and stations of V.P.C.'s and V.P.T.'s will be computed.

The program will therefore compute two different sets of data, one for the parameters such as grades and curve data, and one set for the cross sections. The curve data to be computed consists of the grades of the tangent section and the station/elevation and of the V.P.C.'s and V.P.T.'s. Once this is done, the alignment is fully defined. As stated previously, the centerline elevation, Z_p for each cross section will be computed.

In the MIT series of DTM programs, the basic vertical alignment program is called VA-1 and is essentially that described above. It takes as input data the station and elevation of the origin, terminus, and V.P.I.'s and the lengths of vertical curves; in addition to this data defining the vertical alignment, it also takes as input data the cross section output data of the HA-1 program, i.e. for each section: x , s , y , z and ψ . The output of the VA-1 program



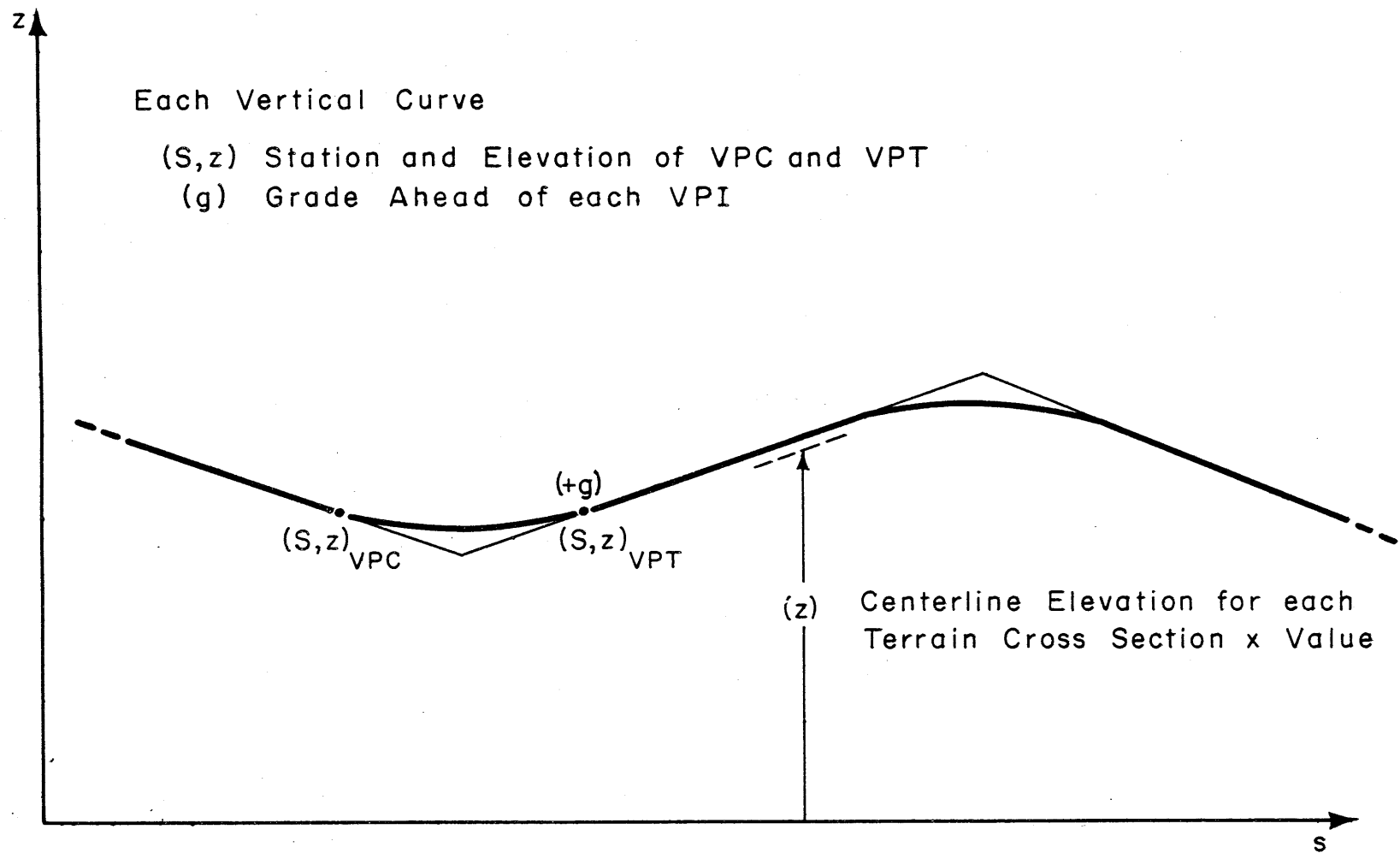
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Each Vertical Curve

(S, z) Station and Elevation of VPC and VPT

(g) Grade Ahead of each VPI

$(S, z)_{VPC}$ $(S, z)_{VPT}$ $(+g)$

(z) Centerline Elevation for each Terrain Cross Section x Value

DTM VERTICAL ALIGNMENT PROGRAMS VA-1
OUTPUT DATA FOR EACH TRIAL GRADE LINE

Fig. VA-2

consists of the station and elevation of the V.P.C.'s and V.P.T.'s, the grades, and, for each section, x , s , y , z , z_p and ψ . The data for each section is punched on one card and contains all the data required for each section in addition to the terrain data for earthwork computations once the template has been defined. Figures 6 and 7 illustrate the input and output of the VA-1 program. Appendix C contains the program Analysis of the VA-1 and VA-2 programs illustrating the basic logic of these two programs.

The output of the HA-1 program contains for each section the station and terrain elevation of a point on the centerline. Taken together, these points form a profile which is used by the engineer in selecting a trial vertical alignment. The problem of selecting a vertical alignment is much simpler than that of selecting a horizontal alignment. For this reason, much work has gone into attempts to have the computer select the grade line. The computer must be given a certain set of conditions to meet before a useful profile can result. The maximum allowable grade must be specified, as must the maximum rate of change of grade. Otherwise, the resulting profile may be acceptable mathematically but completely unacceptable from an engineering standpoint due to excessive grades or insufficient sight distances. There should also be the flexibility of specifying certain control points through which a profile must pass since there are usually interchange or bridge restrictions to be met.

The engineer, in selecting a grade line, is essentially performing a smoothing process. He tries to pick a profile which meets the given specifications, such as maximum allowable grades, and which will yield the minimum balanced earthwork.

A program has been developed at MIT which attempts to select a grade line based on the terrain profile and certain engineering specifications. This program is called the Automatic Profile Design Program, VA-3. The program selects the profile by using a "least-squares" fit of a third degree polynomial to the terrain for a specified distance ahead of the point in question. The input to the program is the output of the HA-1 program and the engineering information. The engineering information consists of length of the range ahead to be used, the maximum allowable grades, the maximum allowable rate of change of grade, and the location and elevation of control points to be met, if any. The output of the program is a profile elevation corresponding to each input point. The alignment is therefore defined by the station and elevation of a great number of points and not by tangents and parabolic curves. Since the program is a radical departure from current practice, extensive testing using a number of different types of data is under way. The results to date have been encouraging and it seems that automatic profile design will soon be a reality.

The selection of a grade line is only one step in the overall automatic highway design problem. It has been the first portion of the problem attacked because it appears to be the simplest. Any techniques or programs developed will eventually be incorporated into the overall design program when this becomes feasible.

EARTHWORK COMPUTATIONS

Once an alignment has been defined, both horizontally and vertically, the earthwork quantities can be computed. Earthwork computations are a standard and important problem. In the DTM System, the problem is basically the same and the same considerations apply. One big decision which must be made is that of selecting the accuracy of computation. If design, or "pay," quantities are desired, the computations will be very precise and detailed. On the other hand, if the study is in the reconnaissance stage, the computed quantities can be fairly approximate without detracting from their usefulness. The intermediate case is that of preliminary location where reconnaissance quantities are not sufficiently accurate and design quantities are not warranted. Of course, design quantities can be used for all three cases, but in two of them, they would involve unnecessary work and computer time. For this reason the problem of earthwork computations is broken down into three categories: reconnaissance, preliminary

and design.

A reconnaissance earthwork program must provide a means of rapidly evaluating the earthwork quantities for a great number of trial lines. Since the earthwork volumes will be used to evaluate the relative merits of alternate lines, they need not be absolutely but only relatively accurate and since a great number of lines will be evaluated, the computations must be relatively simple. Some reconnaissance earthwork programs use as input data only a terrain profile and assume that the terrain is level on both sides of the centerline. This provides a simple method for computing volumes but does not take into account the cross slope of the terrain. Since a side-hill condition is very common in highway location, the reconnaissance program should take into account the terrain slope, if this can be done without unduly complicating the computations. A solution to this would be to use a two point section. The computations would again be fairly simple and would take into account the terrain slope. The difficulty with this solution is that if one point is on the centerline, the other must be to one side, leaving the other side without a defining point. On the other hand, if the terrain points lie on either side of the centerline, there is no centerline profile to use for selecting the grade line.

A further refinement is to use a three point terrain section, one point at the centerline and one on either side. The computations are slightly more complicated but still basically simple. In the DTM Sys-

tem, the three point terrain section can be obtained from the variation of the basic horizontal alignment program which produces two offset profiles in addition to the centerline profile. Such a reconnaissance program has been written and included in the MIT series of DTM programs. This program is called the DTM Reconnaissance Earthwork Program, EW-1.

Since the earthwork calculations for reconnaissance purposes are relatively simple, the EW-1 program includes a vertical alignment routine. This routine is essentially the basic vertical alignment program and serves the same purpose; by including it in the earthwork program, one computer run is eliminated for each trial line.

The EW-1 program uses a very simple design template defined by the width from the centerline to the left hinge point, W_L , the width to the right hinge point, W_R , a slope for use in cut, C_S , and a choice of two slopes, F_S and f_s , for use in fill. The steeper fill slope, F_S , is used when the fill at the hinge point exceeds the criterion, h . Though this template is only an approximation of the actual template that will be used, it is sufficiently accurate^{for} reconnaissance purposes.

The terrain data input to the EW-1 program is the output of the HA-3 program. The two offset points are used to establish the terrain slopes on either side of the centerline. The program computes the intersection of the slopes and the terrain and punches this

information as Baseline y-coordinates and elevations. In addition, it also punches out a code indicating which of the three slopes were used for each side and the distances, along the cross section, from the centerline to each slope intercept point.

The cut and fill volumes between adjacent sections and the accumulated cut and fill volumes are punched out in addition to the mass haul ordinate. Using cross sections at 200 foot intervals, the program computes quantities at the rate of 75 miles per hour.

When the location study has progressed beyond the reconnaissance stage and is in the preliminary location stage, more accurate earthwork computations are desired, though "pay" quantities are still not justified. A program in between the reconnaissance program just described and a very sophisticated program is desired. Such a program must be able to compute fairly accurate quantities at a relatively fast rate. Since three or four, or more, lines may be studied at this stage, an excessive amount of computer time cannot be spent computing earthwork quantities.

The full terrain sections, rather than three point sections, must be used in order to obtain the desired accuracy. However, a very complicated and detailed design template need not be used. A relatively simple template, leading to simple computations can be employed and still yield the desired accuracy.

DTM EW-2

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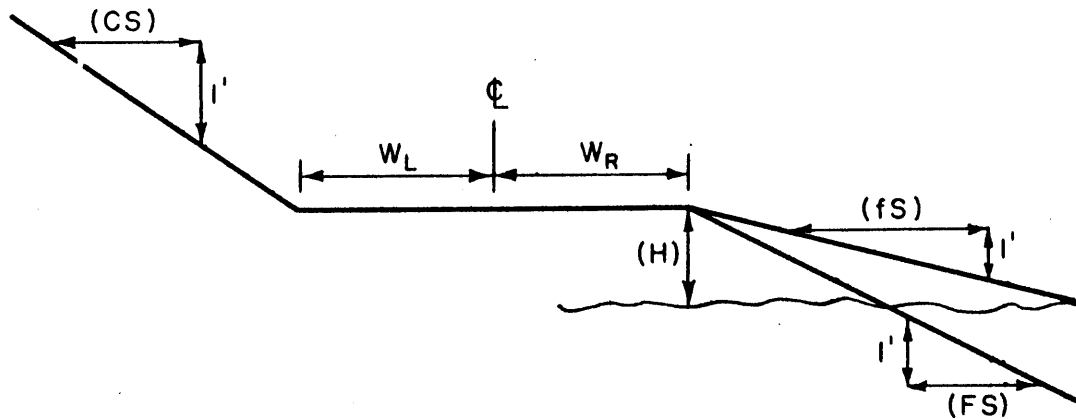
Preliminary Earthwork Program Input
Data - Templet Specifications

Date 8/1/58

Engineer T. H. KAALSTAD

Templet Type T

(W _R) ϕ to Right Hinge Point	1	2	3	4	5	6	7	8	9	10
	0	0	0	0	0	6	6	0	0	0
(W _L) ϕ to Left Hinge Point	11	12	13	14	15	16	17	18	19	20
	0	0	0	0	0	6	6	0	0	0
(fS) Fill Slope for Height of Fill less than (H)	21	22	23	24	25	26	27	28	29	30
	0	0	0	0	0	0	4	0	0	0
(FS) Fill Slope for Height of Fill greater than (H)	31	32	33	34	35	36	37	38	39	40
	0	0	0	0	0	0	2	0	0	0
(CS) Cut Slope	41	42	43	44	45	46	47	48	49	50
	0	0	0	0	0	0	2	0	0	0
Fill Volume Mult. Factor	51	52	53	54	55	56	57	58	59	60
	0	0	0	0	1	2	0	0	0	0
Cut Volume Mult. Factor	61	62	63	64	65	66	67	68	69	70
	0	0	0	0	1	0	0	0	0	0
(H) Fill Height - Slope Decision Criteria	71	72	73	74	75	76	77	78	79	80
	0	0	0	0	0	1	0	0	0	0



12 punch in cc 1, 10, 20, 30, 40, 60, 70, and 80
11 punch in cc 50
All columns must be punched

REMARKS _____

Such a program has been included in the MIT series and is called Preliminary Earthwork Program, EW-2. The design template for this program is the same for EW-1 though the program uses the full DTM sections. Figure 8 shows the template specification data for a typical road. The output is essentially the same as for EW-1 though the computed values are much more accurate due to the increased terrain information. The running time for the program is dependent on the number of sections and the number of points per section; but assuming cross sections every 100 feet and an average of 30 points per section, the program will compute 10 miles of earthwork per hour. Some questions arose as to whether or not the program was accurate enough for preliminary location. Extensive tests were made comparing volumes obtained from EW-2 with conventional "pay" quantities. These tests indicated conclusively that the volumes were within 5 per cent of "pay" quantities. Appendix D contains the program analysis for the EW-2 Program, showing how a simplified template makes it possible to use basic logic for the earthwork program.

The problem of computing design earthwork quantities is a major one. The problem can normally be broken down into two major parts: selecting and fitting the template to the terrain, and computing the cross sectional areas.

The designer, in establishing the template for a particular section, follows a general set of rules. However, in a great number of cases, the general rules do not adequately cover the existing situation and the engineer makes an exception. An example of this is the case where, due to right-of-way limitations, the engineer uses a 2 : 1 slope whereas he would normally use no slope steeper than 2-1/2:1. Another example is that of the use of benches in deep cuts. These benches are not generally established according to any set rules since they are based partly on soil conditions, depth of cut, and experience. Since the computer can neither exercise engineering judgement, nor read the engineer's mind, the selection of the proper template presents many problems. Another factor complicating the problem is the variation in the design standards of the various state highway departments. A computer program that could meet the design requirements of all 50 states would be performing a Herculean task.

The problem, although great, is not unsolvable. By setting up a complete and flexible set of design criteria, it is possible to have the computer select the proper template for nearly all the conditions encountered. There will still be some cases where the engineer will overrule the computer's selection but these instances cannot be eliminated for the reasons mentioned previously.

The cross-sectional area computations become more involved as

the template becomes more complicated. However, the procedure, though it can be very complicated, is essentially simple. Since the mathematics of the problem are basically simple, the procedure is complicated mainly in a logical sense. For this reason, the cross sectional area computation can be solved.

Setting up the standards for an all-inclusive earthwork program is a major undertaking in itself. If the program is to be used throughout the U.S., the criteria of the 50 states should be met. Determining the design requirements for each of the states is a major task. Since this has not been done by the author, the ideal program will be defined only in general terms.

Since a design template is basically symmetrical about some reference line, only one half of it will be discussed. The template can be divided into three sections: the first section is that which remains constant from section to section, the second section is from the end of the first to the hinge point, the third is everything beyond the hinge point.

The first segment, sometimes called the basic template, will include part of the median, and the inside shoulder, if the reference line is along the median and the pavement to the shoulder. This portion will usually remain constant from section to section and will be composed of a number of segments of varying slope and length. The number of segments may vary from one to over a dozen though

normally there will be five or less. In order to have a very flexible template, it should therefore have at least five segments on each side. These segments would be defined by horizontal length and slope. The full basic template would therefore be a minimum of ten segments defined by horizontal length and slope. The section of the template from the end of the basic template to the hinge point includes the shoulder and any ditches. This section will have to be defined for cut and for fill since it will vary depending on the condition. In order to have a flexible template, this second portion should be defined for each allowable slope. If three fill slopes and three cut slopes are allowed, this would mean that the second section would be defined in six different ways. This section will normally be short but will require a minimum of three segments if a ditch is used. For this reason, it will be assumed that four segments, defined by slope and horizontal distance are used.

From the hinge point to the final slope intercept, the template is defined by a slope or a slope with benches. If no benches are used, there must be a choice of slopes for both cut and fill. Though any number of slopes may be used depending on the terrain, the great majority of cases can be handled if a choice of three cut slopes and a choice of three fill slopes is provided. Some criteria must also be provided to determine which slope to use under any particular condition. A fairly common method is to assume

the flattest slope, determine the slope intercept and then compare the distance out to the slope intercept with some criterion. If the distance is greater than the criterion, the middle slope is assumed and the process is repeated. If the distance is again greater than the second criterion, the steepest slope is used. Since this method is used for both cut and fill, four different criteria must be specified, two for cut and two for fill. When benches are to be used, some specifications must be established to determine when and how they will be used.

One method of defining the conditions would be to specify that, using the steepest cut slope, a bench of y feet wide will be made every x feet vertically if the depth of cut exceeds z feet. x , y and z would have to be determined by the engineer and could probably be selected such that the benches established by the computer would meet the requirements. In many cases, however, the engineer would have to reestablish these benches when they did not meet with his approval.

In the MIT series of DTM programs, the design earthwork program is called the Design Earthwork Program, EW-3. This program has three sets data: the DTM cross sections, the output of the vertical alignment program, VA-1 which relates the alignment to the cross sections, and the data defining the template. The template is defined by seven segments each side of the reference line for the basic template, three segments in cut and two in fill

for the region between the basic template and the hinge point, and a choice of three fill or three cut slopes. No provision is made for benching. The criteria for the selection of slopes is that described above and requires four parameters.

The output of the program is divided into two categories: template data and volume data. The template data gives, for each side, the baseline y coordinate of the slope stake, and its elevation, and the slope used. The volume data gives the cut and fill volumes between sections, the accumulated cut and fill volumes and the mass haul ordinate. The program will also punch out additional information, such as cross sectional areas on demand.

When a program is finally written for the automatic selection of a highway alignment, it will probably require some form of earthwork routine. The type of routine required will depend on which phase of location the program is performing and perhaps will require all three types of earthwork programs, reconnaissance, preliminary and design. Independent of whatever routines are finally required, the experience gained in writing and using the earthwork programs will prove invaluable and perhaps the routines themselves may be used.

PLOTTING DTM OUTPUT

A digital computer is a device capable of accepting great quantities of input data. It is equally capable of producing great quantities of output data. One of the difficulties associated with using computers is that their output is in numerical form though often, a graphical representation is desired. For many applications, numerical answers are desirable and directly useful, but on the other hand, a profile in numerical form means little to a highway engineer.

The DTM System has one feature which greatly simplifies plotting the output. All the input and output data is referenced to an auxilliary coordinate system. As will be shown, this feature provides a powerful means for analyzing and comparing alternate trial lines.

The input and output data of the horizontal alignment programs provides all the information necessary for plotting in plan view the centerline. The standard curve data, such as intersection angle and tangent length, can also be added to the plot. Shoulder lines, ditch lines, and/or right-of-way lines can be plotted from the output of the horizontal offset line program. The only additional data required for providing a complete plan view of the alignment is the slope stake information. These construction limits are included in the output of the earthwork programs and since this data is also referenced to the baseline, it can be easily added to the plan produced

from the output of the horizontal alignment programs.

If the lanes of a divided highway are processed separately as individual roadways, they can still be easily plotted on the same plan view. This is easily done since all the data is in Baseline coordinates.

The output of the basic horizontal alignment program includes the data for plotting a profile of the terrain along the centerline. This profile would normally be plotted as z (elevation) versus S (station). However, the profile can also be plotted as z versus Baseline x . Using the Baseline as a reference provides the opportunity for plotting the profiles of various trial lines against a common reference. The distortion introduced by using x instead of S will normally be slight and quickly adjusted to.

When the output of the vertical alignment program is added to the profile plot a complete plot of the vertical alignment, suitable for use in a set of plans, is obtained.

As mentioned previously, the ~~slope~~ stake information obtained from the earthwork program can be added to the plot of the horizontal data. In addition to this, the mass haul ordinate can be plotted versus x . This provides the engineer with the information he needs for selecting a different profile or even a different horizontal alignment. When the mass haul ordinates for different trial lines are plotted together, they provide an indication of the possible

effects of a horizontal line shift.

As has been pointed out, the DTM System provides all the data necessary for producing a complete set of design plans and profiles.

Up to this point, nothing has been said of the means available for producing all these plots. Manual methods can, of course, be used, but the new line and point plotters must also be considered.

There has been recently introduced on the market, instruments which will produce line plots from numerical information. These new machines, now generally available, will also print information along the edges of the plot in some cases. The input data can be manually entered from a keyboard or can be on punched paper tape, or punched cards. Since the output of the DTM programs is on punched cards or tape, it would be a simple step to use them as input to a line plotter to produce whatever plans are desired. As of yet, no extensive use of line plotters for plotting DTM output has been made. However, some studies have been initiated and the outlook is bright.

Point plotters have been generally available for some time though they have not been extensively used in highway engineering. Some of the plotters can plot a number of different symbols and some can print information next to the plotted points. Most of the plotters will take punched cards or punched tape as input in addition to manual entries from a keyboard. The point plotters can plot faster than the

line plotters and some of them can be obtained at a lower price. The end product desired is usually a line plot of some form but in many instances, this can be approximated by a point plot having a high density of points. Point plotters have not yet been used to plot DTM output but they are also being studied.

A device that is coming into use as a point plotter is the standard accounting tabulator. This machine is card operated and normally prints a line at a time. The IBM 407 tabulator has 120 printing positions at 1/10 inch increments. When the tabulator is used as a point plotter, the width (12 inches) is used to plot z (or y) and x (or s) is plotted on the length. Since continuous forms are used on these machines, the plots can be of indefinite length in one dimension though limited in the other. Extensive use of the IBM 407 tabulator as a point plotter for DTM output is being made at the Michael Baker, Jr., Inc. Electronic Computation Center in Rochester, Pennsylvania. The results, to date, have been very encouraging and the work is continuing. The main advantage of the tabulator as a point plotter is its availability. All punched card computer installations must have some form of tabulator available for listing the punched cards. As a matter of fact, at this writing, all IBM 650 installations used for highway engineering work have a 407 tabulator. This means that all these installations have a machine which they can use as a point plotter. Admittedly, the tabulator is

not as good a point plotter as machines designed for this purpose. But since it is already available, it can be efficiently used for this purpose.

It is merely a matter of time before extensive use is made of both point and line plotters for highway engineering work. This application is now in its initial stages but is progressing rapidly so that in five years, point and line plotters will be common tools of the civil engineer.

SUMMARY

The Digital Terrain Model Principle, though a rather new development, is now an accomplished fact. The problem of applying the DTM principle to highway location has been partially solved. A series of computer programs utilizing the DTM for highway work has been written at the MIT Photogrammetry Laboratory by the author and colleagues. Though these programs are a significant advance in the field of highway engineering, it should be remembered that they are only first attempts. For the most part, the existing programs serve the desired purpose, but in some respects, they fall somewhat short of the ideal.

The experience acquired in developing the first series of programs and the practice gained in using them must be used to determine how these programs can be improved and what new programs are desired. The library of computer programs using the DTM for highway engineering must never be considered complete but must be continually revised and expanded as time progresses.

The use of the DTM for highway location now appears to be a clear-cut application. However, it is very likely that as more use is made of the DTM, new and different applications in the highway field will be developed. It is impossible to predict, at this point, what the DTM can lead to if the present rate of progress is continued, but it can be safely said that it will, at least, enable the engineer to design better roads.

APPENDIX A

The Engineering Instructions, Operating Instructions and Program Analysis for the DTM Terrain Data Edit Program, TD-1. This writeup demonstrates the format of the DTM System Manual and the care that must go into a computer program writeup to make the program truly useful.

DTM TERRAIN DATA EDIT PROGRAM TD-1GENERAL DESCRIPTIONEngineering Procedure

1. To insure that the cards of the terrain data deck are in proper sequence, they may be edited by the computer. This eliminates unnecessary error stops occurring when the terrain data is being used in the highway programs.

2. When the reliability of the terrain data deck is questioned; the engineer may also request that the deck be listed for comparison with the source of data.

Program Description

1. The purpose of TD-1 is to edit the terrain data deck for incorrect sequencing of data due to mistakes in punching or assembling the cards.

2. TD-1 checks for the following types of errors:

a. x not increasing - if x value on a Beginning-of-Line card is not greater than the x value of the preceding Beginning-of-Line card.

b. not same x - if the x value on a Terrain Data card is not the same as the x value on the preceding Beginning-of-Line card.

c. y not increasing - if the y values on the Terrain Data cards are not in increasing order.

d. blank and multiply-punched columns.

Computer Input Data

The terrain data deck.

Computer Output Data

If there are no errors of the type outlined above, there will be no output. In the presence of errors of the first three types, error cards will be punched defining the errors as follows.

a. If the x value of a Beginning-of-Line card is not greater than that of the preceding Beginning-of-Line card, a card is punched reading

ERROR X NOT GREATER X PRIOR IS XXXXXXXX.XXX

where the x value is that of the previous Beginning-of-Line card. This means that one or more cards are out of order or that a card has been mispunched.

b. If the x value on a Terrain Data card does not agree with the x value on the Beginning-of-Line card for the cross section, a card is punched reading

ERROR NOT SAME X X PRIOR IS XXXXXXXX.XXX

where the x value is that of the Beginning-of-Line card. This means that a Beginning-of-Line card was omitted, a card is out of order, or a card was mispunched.

c. If the y values of a pair of points are not increasing, a card is punched reading

ERROR Y NOT INCREASING X IS XXXXXXXX.XXX

where the x value is that of the cross section being read in. This means that the points were not punched in increasing order, a card was mispunched, or a card is out of order.

* * * *

Errors in the terrain data deck which are detected by the Edit Program should be corrected before the data is used in the other programs for computations.

DTM TERRAIN DATA EDIT PROGRAM TD-1OPERATING INSTRUCTIONS

1. 533 Control Panel - Standard DTM
2. Console Switches
 - ERROR - stop
 - OVERFLOW - stop
 - DISPLAY - any
 - CONTROL - run
 - ADDR. SELECTION - any
 - HALF CYCLE - run
 - PROGRAMMED - run
 - STORAGE ENTRY - 70 1951 1600 +
3. Order of Cards
 - a. Program Deck
 - Containing: Drum Zero (2 cards)
 - 4/card Loader (3 cards)
 - 4/card Program Deck
 - b. Terrain Data Deck
 - (The first and last cards must be Beginning-of-Line cards.)
4. Operation
 - a. Computer Reset
 - b. Program Start
 - c. 533 Read Start
 - d. 533 Punch Start
 - e. End of file when needed
5. Error Stops

There are no programmed stops. There are no read stops. The computer will stop on a blank column or a multiply-punched column. If this occurs, one or more of the CHECKING lights will go on. Restart: The cards are removed from the read hopper. The read start key is held down until all remaining cards are run through the read feed. The mispunched card is the fourth from the back. It should be marked. The program is started at next section by placing the cards in the read hopper and pushing the Computer Reset, Computer Start, Read Start, and Punch Start keys.

PROGRAM ANALYSISDTM TERRAIN DATA EDIT PROGRAM TD-1GENERAL DESCRIPTION

The purpose of TD-1 is to edit the terrain data for incorrect sequencing of data due to mistakes in recording the data or punching and assembling the cards.

TD-1 checks for the following types of errors:

a) x not increasing. If the x value of a Beginning-of-Line card is not greater than the x value of the preceding Beginning-of-Line card.

b) not same x. If the x value on a Terrain Data card is not the same as the x value on the preceding Beginning-of-Line card.

c) y not increasing. If the y values on Terrain Data cards are not in increasing order.

DEFINITION OF TERMS

x_j the x value of a cross section

y_i, z_i the y and z values of a point on a cross section

Beginning-of-Line card (BLC): The first card of a cross section. It is a header and contains only the identification and the x-value of the cross section.

Data card: These cards contain the terrain data. Each card has from one to four data points.

INPUT TO TD-1

The input to TD-1 consists of the terrain data deck, It is shown as it appears to the computer as opposed to the way it is punched on the cards.

Beginning-of-Line Cards

Word 1	0008999998+	the 8 in digit 7 indicates that this is terrain data card. The 8 in digit 1 indicates that it is a BLC.
2	0000xxxxx.x+	Baseline x value of cross section
3-10		Not used

Data Cards

Word 1	0008xxxxxx9+	
Digit 1	9	Indicates Data Card (11 punch CC 12)
2	9	CC 13-Blank
	8	11 or 12 punch
3	9	CC 30-Blank
	8	Blank or 12 punch
4	9	CC 47-Blank
	8	11 or 12 punch
5	9	CC 64-Blank
	8	11 or 12 punch
6	9	CC 13 (Succeeding card)-Blank
	8	12 punch
Word 2	0000xxxxx.x±	The x value of this section. The sign will be minus if there is an 11-punch in CC 13.
Word 3	yyyy.yzzzz.z±	The y-z coordinates of the first point on the card. The sign will be minus if there is an 11 punch in CC 30.
Word 4	yyyy.yzzzz.z±	The y-z coordinates of the second point on the card. The sign will be minus if there is an 11 punch in CC 47.
Word 5	yyyy.yzzzz.z±	The y-z coordinates of the third point on the card. The sign will be minus if there is an 11 punch in CC 64.
Word 6	yyyy.yzzzz.z+	The y-z coordinates of the fourth point on the card
Words 7-10		Not used

OUTPUT OF TD-1

The output of TD-1 is "error" cards indicating that violations of the restrictions have been detected. There are 10 different error routines (see Block Diagram). Two of the routines refer to errors involving x, the 8 others refer to errors involving a y-z word.

Only three different error cards are used: two for x and one for y-z. They correspond to the three types of errors detected.

ERROR TYPE 1

Action: The alphabetic information for this type is stored in A0001 to A0006 and says:

ERROR x NOT INCR x PRIOR is

When this type of error is detected the x value of the preceding BLC is stored in word 7 and the card is punched.

Reason: This error is due to having the cards out of sort or to having two BLC's with the same x value. This could only happen if a data card had an 11 punch in CC 12.

ERROR TYPE 2

Action: The alphabetic information for this type is stored in B0001 to B0006 and says

ERROR x NOT SAME x PRIOR is

When this error occurs the x-value of the preceding BLC is stored in word 7 and the card is punched.

Reason: The x value on a data card does not agree with the x value on the preceding BLC. This will happen if the cards are out of sort or if a BLC is missing.

ERROR TYPE 3

Action: The alphabetic information for this type of error is stored in C0001 to C0006 and says:

ERROR y NOT INCR yz AND x ARE

When this type of error is detected (it can refer to any of four points on a card) the yz value is put in word 7 and the x value of the section is put in word 8, then the card is punched.

Reason: The y coordinates of points within a section are not in order of increasing magnitude. This can be a recording error or a key punch error.

OUTPUT CARD FORMATS

The output routines of TD-1 were originally set up for a control panel having a special alphabetic output format. However, a last minute change was made in the control panel and this special format was eliminated.

At present the 80-80 format is used for the alphabetic output. This means that there are five blank spaces between each group of five alphabetic characters. Therefore the alphabetic information is spread from CC 1 to CC 60. Word 7 is in CC 61 to 70 and word 8 is in CC 71 to 80.

Due to this format the output is somewhat spread when listed on a 407 using 80-80 control panel though it is still readable.

BLOCK DESCRIPTION

(See Fig. 2-10:1)

- Block 1 The value of x previous is initialized by setting it to -1.
- 2 This is the read instruction used for all cards. Since the first card is read in using the console instruction. This block is by-passed.
 3. The card read in is tested to determine if it is a BLC (8 in digit 1 of word 1).
 4. If the card is a BLC the routine is initialized for a new section by setting the value of y previous to 0.
 5. The x value on the card is compared with that on the previous BLC. If x is not increasing control goes to the error routine (Block 5A).
 6. The new x value is stored.
 7. If the card read in was not a BLC the x value on the card is compared with the x value of the preceding BLC. If they do not agree control goes to the error routine (Block 7A).

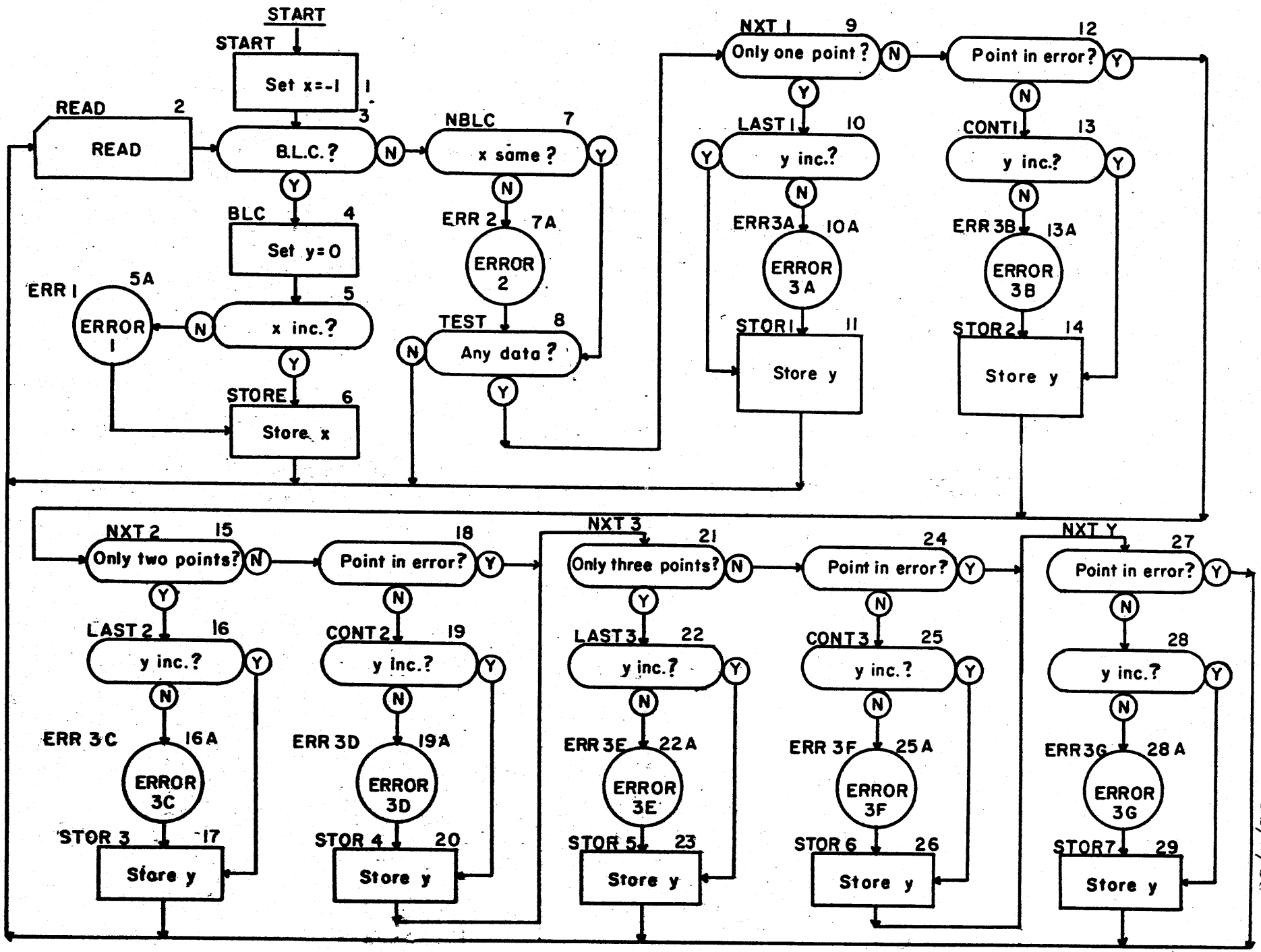


Fig. 2-10:1

- Block 8 If there is an 11 punch in CC 13 there are no points on the card. This is indicated by a 9 in digit 2. If there are no points control returns to the READ instructions.
- 9,12 CC 30 can be blank, have an 11 punch indicating that there is only one point on the card, or have a 12 punch indicating that the first point is in error. If CC 30 is blank (9 in digit 3, word 1) control goes to Block 13.
- If CC 30 has an 11 punch (8 in digit 3, word 1 and minus sign in word 3) control goes to Block 10.
- If CC 30 has a 12 punch (8 in digit 3, word 1 and a plus sign in word 3) control goes to Block 15.
- 10,13 These two Blocks perform the same function: they check to determine if the y's are in increasing order
- 10A,13A Error routines for the errors detected in Blocks 10 and 13 respectively.
- 11,14 The y value is saved to be used in testing the next point.
- 15-20, 21-26 Blocks 9-14 could be used over again to check the second and third points. This would involve address modification but since storage is no problem and only three points are involved the complete loop is repeated three times.
- 27 If the fourth point on a card is in error there will be a 12 punch in CC 13 of the next card. If this is the case there will be an 8 in digit 6 of word 1.
- 28 The fourth point is tested for increasing y,
- 28A This is the routine for an error in Block 28
- 29 The y value of the fourth point is stored for testing the first point on the next card.

SUBROUTINES

No subroutines are used.

RESTRICTIONS

There are no restrictions on the program.

SCALING AND SIGNIFICANT DIGITS

Does not apply

MATHEMATICAL ANALYSIS

Does not apply.

			1 1		TERRAIN DATAE ITIG PROGRAM
			2 1		TD 1 AG 1 958
			3	REG	R1951 1970
			4	REG	Z1977 1986
			5	REG	A0027 0036
			6	REG	B0077 0086
			7	REG	C0127 0136
			8	SYN	START 1600
			9	SYN	STORE 0100
			10	SYN	XOK 0200
			11	SYN	STOR1 0300
			12	SYN	HLT1 0400
			13	SYN	STOR3 0500
			14	SYN	HLT2 0600
			15	SYN	STOR5 0700
			16	SYN	HLT3 0800
			17	SYN	HLT4 0900
0027	65 7979 7679		18	A0001 ALF	ERROR SOAP2
0028	87 0075 7683		19	A0002 ALF	X NOT SOAP2
0029	69 7563 7900		20	A0003 ALF	INCR SOAP2
0030	00 0000 0087		21	A0004 ALF	X SOAP2
0031	77 7969 7679		22	A0005 ALF	PRIOR SOAP2
0032	69 8200 0000		23	A0006 ALF	IS SOAP2
0034	00 0000 0000		24	A0008 00	0000 0000
0036	00 8000 0008		25	A0010 00	8000 0008
0077	65 7979 7679		26	B0001 ALF	ERROR SOAP2
0078	87 0075 7683		27	B0002 ALF	X NOT SOAP2
0079	82 6174 6500		28	B0003 ALF	SAME SOAP2
0080	00 0000 0087		29	B0004 ALF	X SOAP2
0081	77 7969 7679		30	B0005 ALF	PRIOR SOAP2
0082	69 8200 0000		31	B0006 ALF	IS SOAP2
0084	00 0000 0000		32	B0008 00	0000 0000
0086	00 8000 0008		33	B0010 00	8000 0008
0127	65 7979 7679		34	C0001 ALF	ERROR SOAP2
0128	88 0075 7683		35	C0002 ALF	Y NOT SOAP2
0129	69 7563 7900		36	C0003 ALF	INCR SOAP2
0130	00 0000 8889		37	C0004 ALF	YZ SOAP2
0131	61 7564 0087		38	C0005 ALF	AND X SOAP2
0132	61 7965 0000		39	C0006 ALF	ARE SOAP2
0136	00 8000 0008		40	C0010 00	8000 0008
0000	00 0000 0001		41	-IAONE 00	0000 0001
0050	24 0033 0186		42	ERR1 STD	A0007
0186	71 0027 0177		43	PCH	A0001
0177	01 0001 0100		44	HLT	0001 STORE
0150	24 0083 0236		45	ERR2 STD	B0007
0236	71 0077 0227		46	PCH	B0001
0227	01 0002 0200		47	HLT	0002 XOK
0250	24 0133 0286		48	ERR3A STD	C0007
0286	69 0039 0042		49	LDD	X1
0042	24 0134 0037		50	STD	C0008

0037	71	0127	0277	51		PCH	C0001	
0277	01	0031	0300	52		HLT	0031	STOR1
0350	69	0003	0006	53	ERR3B	LDD	Y1	
0006	24	0133	0336	54		STD	C0007	
0336	69	0039	0092	55		LDD	X1	
0092	24	0134	0087	56		STD	C0008	
0087	71	0127	0327	57		PCH	C0001	
0327	01	0031	0400	58		HLT	0031	HLT1
0400	69	1953	0056	59	HLT1	LDD	R0003	STOR2
0450	24	0133	0386	60	ERR3C	STD	C0007	
0386	69	0039	0142	61		LDD	X1	
0142	24	0134	0137	62		STD	C0008	
0137	71	0127	0377	63		PCH	C0001	
0377	01	0032	0500	64		HLT	0032	STOR3
0550	69	0003	0106	65	ERR3D	LDD	Y1	
0106	24	0133	0436	66		STD	C0007	
0436	69	0039	0192	67		LDD	X1	
0192	24	0134	0187	68		STD	C0008	
0187	71	0127	0427	69		PCH	C0001	
0427	01	0032	0600	70		HLT	0032	HLT2
0600	69	1954	0007	71	HLT2	LDD	R0004	STOR4
0650	24	0133	0486	72	ERR3E	STD	C0007	
0486	69	0039	0242	73		LDD	X1	
0242	24	0134	0237	74		STD	C0008	
0237	71	0127	0477	75		PCH	C0001	
0477	01	0033	0700	76		HLT	0033	STOR5
0750	69	0003	0156	77	ERR3F	LDD	Y1	
0156	24	0133	0536	78		STD	C0007	
0536	69	0039	0292	79		LDD	X1	
0292	24	0134	0287	80		STD	C0008	
0287	71	0127	0527	81		PCH	C0001	
0527	01	0033	0800	82		HLT	0033	HLT3
0800	69	1955	0008	83	HLT3	LDD	R0005	STOR6
0850	69	0003	0206	84	ERR3G	LDD	Y1	
0206	24	0133	0586	85		STD	C0007	
0586	69	0039	0342	86		LDD	X1	
0342	24	0134	0337	87		STD	C0008	
0337	71	0127	0577	88		PCH	C0001	
0577	01	0034	0900	89		HLT	0034	HLT4
0900	69	1956	0009	90	HLT4	LDD	R0006	STOR7
1600	69	0000	0053	91	START	LDD	IAONE	
0053	24	0039	1961	92		STD	X1	R0011
0392	70	1951	1961	93	READ	RD1	R0001	R0011
1961	67	1952	0057	94	R0011	RAM	R0002	
0057	69	1951	0004	95		LDD	R0001	
0004	91	0107	0059	96		BD1	BLC	NBLC
0107	21	0003	0256	97	BLC	STU	Y1	
0256	16	0039	0043	98		SLO	X1	

0043	46	0050	0047	99		BMI	ERR1	
0047	45	0100	0050	100		NZE	STORE	ERR1
0100	15	8001	0157	101	STORE	ALO	8001	
0157	20	0039	0392	102		STL	X1	READ
0059	16	0039	0093	103	NBLC	SLO	X1	
0093	45	0150	0200	104		NZE	ERR2	XOK
0200	69	1951	0054	105	XOK	LDD	R0001	
0054	92	0207	0109	106		BD2	TEST	NXT1
0207	60	1952	0257	107	TEST	RAU	R0002	
0257	46	0392	0109	108		BMI	READ	NXT1
0109	69	1951	0104	109	NXT1	LDD	R0001	
0104	93	0307	0159	110		BD3	TEST1	CONT1
0307	60	1953	0357	111	TEST1	RAU	R0003	
0357	46	0010	0011	112		BMI	LAST1	NXT2
0010	10	0003	0407	113	LAST1	AUP	Y1	
0407	46	0300	0250	114		BMI	STOR1	ERR3A
0300	67	1953	0457	115	STOR1	RAM	R0003	
0457	20	0003	0392	116		STL	Y1	READ
0159	60	0003	0507	117	CONT1	RAU	Y1	
0507	11	1953	0557	118		SUP	R0003	
0557	46	0056	0350	119		BMI	STOR2	ERR3B
0056	24	0003	0011	120	STOR2	STD	Y1	NXT2
0011	69	1951	0154	121	NXT2	LDD	R0001	
0154	94	0607	0209	122		BD4	TEST2	CONT2
0607	60	1954	0259	123	TEST2	RAU	R0004	
0259	46	0012	0013	124		BMI	LAST2	NXT3
0012	10	0003	0657	125	LAST2	AUP	Y1	
0657	46	0500	0450	126		BMI	STOR3	ERR3C
0500	67	1954	0309	127	STOR3	RAM	R0004	
0309	20	0003	0392	128		STL	Y1	READ
0209	60	0003	0707	129	CONT2	RAU	Y1	
0707	11	1954	0359	130		SUP	R0004	
0359	46	0007	0550	131		BMI	STOR4	ERR3D
0007	24	0003	0013	132	STOR4	STD	Y1	NXT3
0013	69	1951	0204	133	NXT3	LDD	R0001	
0204	95	0757	0409	134		BD5	TEST3	CONT3
0757	60	1955	0459	135	TEST3	RAU	R0005	
0459	46	0062	0063	136		BMI	LAST3	NXT4
0062	10	0003	0807	137	LAST3	AUP	Y1	
0807	46	0700	0650	138		BMI	STOR5	ERR3E
0700	67	1955	0509	139	STOR5	RAM	R0005	
0509	20	0003	0392	140		STL	Y1	READ
0409	60	0003	0857	141	CONT3	RAU	Y1	
0857	11	1955	0559	142		SUP	R0005	
0559	46	0008	0750	143		BMI	STOR6	ERR3F
0008	24	0003	0063	144	STOR6	STD	Y1	NXT4
0063	69	1951	0254	145	NXT4	LDD	R0001	
0254	96	0392	0609	146		BD6	READ	

0609	60	0003	0907	147	RAU	Y1	
0907	11	1956	0061	148	SUP	R0006	
0061	46	0009	0850	149	BMI	STOR7	ERR3G
0009	24	0003	0392	150	STOR7	STD	Y1
				151	PAT		READ

0000	0000000000	0450	500	0000000001	0950	1000	1111111111	1450	1500	1101111111	1950
0001	1111111111	0451	501	1111111111	0951	1001	1111111111	1451	1501	1111111110	1951
0002	1111111111	0452	502	1111111111	0952	1002	1111111111	1452	1502	1111111110	1952
0003	0011111111	0453	503	1111111111	0953	1003	1111111111	1453	1503	1111111110	1953
0004	0000001111	0454	504	1111111111	0954	1004	1111111111	1454	1504	1111111110	1954
0005	1111111111	0455	505	1111111111	0955	1005	1111111111	1455	1505	1111111110	1955
0006	0000001111	0456	506	1111111111	0956	1006	1111111111	1456	1506	1111111110	1956
0007	0000000000	0457	507	0000000001	0957	1007	1111111111	1457	1507	1111111110	1957
0008	0111111111	0458	508	1111111111	0958	1008	1111111111	1458	1508	1111111110	1958
0009	0000000000	0459	509	0001111111	0959	1009	1111111111	1459	1509	1111111110	1959
0010	0111111111	0460	510	1111111111	0960	1010	1111111111	1460	1510	1111111110	1960
0011	0011111111	0461	511	1111111111	0961	1011	1111111111	1461	1511	1111111110	1961
0012	0011111111	0462	512	1111111111	0962	1012	1111111111	1462	1512	1111111110	1962
0013	0011111111	0463	513	1111111111	0963	1013	1111111111	1463	1513	1111111110	1963
0014	1111111111	0464	514	1111111111	0964	1014	1111111111	1464	1514	1111111110	1964
0015	1111111111	0465	515	1111111111	0965	1015	1111111111	1465	1515	1111111110	1965
0016	1111111111	0466	516	1111111111	0966	1016	1111111111	1466	1516	1111111110	1966
0017	1111111111	0467	517	1111111111	0967	1017	1111111111	1467	1517	1111111110	1967
0018	1111111111	0468	518	1111111111	0968	1018	1111111111	1468	1518	1111111110	1968
0019	1111111111	0469	519	1111111111	0969	1019	1111111111	1469	1519	1111111110	1969
0020	1111111111	0470	520	1111111111	0970	1020	1111111111	1470	1520	1111111110	1970
0021	1111111111	0471	521	1111111111	0971	1021	1111111111	1471	1521	1111111111	1971
0022	1111111111	0472	522	1111111111	0972	1022	1111111111	1472	1522	1111111111	1972
0023	1111111111	0473	523	1111111111	0973	1023	1111111111	1473	1523	1111111111	1973
0024	1111111111	0474	524	1111111111	0974	1024	1111111111	1474	1524	1111111111	1974
0025	1111111111	0475	525	1111111111	0975	1025	1111111111	1475	1525	1111111111	1975
0026	1111111111	0476	526	1111111111	0976	1026	1111111111	1476	1526	1111111111	1976
0027	0000000000	0477	527	0011111111	0977	1027	1111111111	1477	1527	1111111110	1977
0028	0001111111	0478	528	1111111111	0978	1028	1111111111	1478	1528	1111111110	1978
0029	0001111111	0479	529	1111111111	0979	1029	1111111111	1479	1529	1111111110	1979
0030	0001111111	0480	530	1111111111	0980	1030	1111111111	1480	1530	1111111110	1980
0031	0001111111	0481	531	1111111111	0981	1031	1111111111	1481	1531	1111111110	1981
0032	0001111111	0482	532	1111111111	0982	1032	1111111111	1482	1532	1111111110	1982
0033	0001111111	0483	533	1111111111	0983	1033	1111111111	1483	1533	1111111110	1983
0034	0001111111	0484	534	1111111111	0984	1034	1111111111	1484	1534	1111111110	1984
0035	0001111111	0485	535	1111111111	0985	1035	1111111111	1485	1535	1111111110	1985
0036	0000000000	0486	536	0011111111	0986	1036	1111111111	1486	1536	1111111110	1986
0037	0000000111	0487	537	1111111111	0987	1037	1111111111	1487	1537	1111111111	1987
0038	1111111111	0488	538	1111111111	0988	1038	1111111111	1488	1538	1111111111	1988
0039	0111111111	0489	539	1111111111	0989	1039	1111111111	1489	1539	1111111111	1989
0040	1111111111	0490	540	1111111111	0990	1040	1111111111	1490	1540	1111111111	1990
0041	1111111111	0491	541	1111111111	0991	1041	1111111111	1491	1541	1111111111	1991
0042	0000000011	0492	542	1111111111	0992	1042	1111111111	1492	1542	1111111111	1992
0043	0011111111	0493	543	1111111111	0993	1043	1111111111	1493	1543	1111111111	1993
0044	1111111111	0494	544	1111111111	0994	1044	1111111111	1494	1544	1111111111	1994
0045	1111111111	0495	545	1111111111	0995	1045	1111111111	1495	1545	1111111111	1995
0046	1111111111	0496	546	1111111111	0996	1046	1111111111	1496	1546	1111111111	1996
0047	0111111111	0497	547	1111111111	0997	1047	1111111111	1497	1547	1111111111	1997
0048	1111111111	0498	548	1111111111	0998	1048	1111111111	1498	1548	1111111111	1998
0049	1111111111	0499	549	1111111111	0999	1049	1111111111	1499	1549	1111111111	1999

001

TD I AVATLABILITY TABLE

APPENDIX B

Program Analysis of DTM Horizontal Alignment Programs HA-1, HA-2, HA-3 and HA-4. These programs are examples of the type necessary to solve the horizontal geometry problems of the DTM.

PROGRAM ANALYSISDTM BASIC HORIZONTAL ALIGNMENT PROGRAM HA-1GENERAL DESCRIPTIONEngineering Procedure

1. With the aid of a standard photogrammetric map, aerial photographs, and other location factor data, the engineer selects the trial alignments to be numerically evaluated. Normally these will be plotted on the map and standard procedure followed except that more than the usual number of lines will be plotted and actually computed in detail.

2. The state plane coordinates of the origin, each P.I. and the terminus of each line are scaled from the map plot. The centerline station of the origin and the radius of curvature associated with each P.I. are designated by the engineer.

Program Description

1. The purpose of the HA-1 program is to compute the geometry of the centerline and to geometrically relate the alignment to the terrain data.

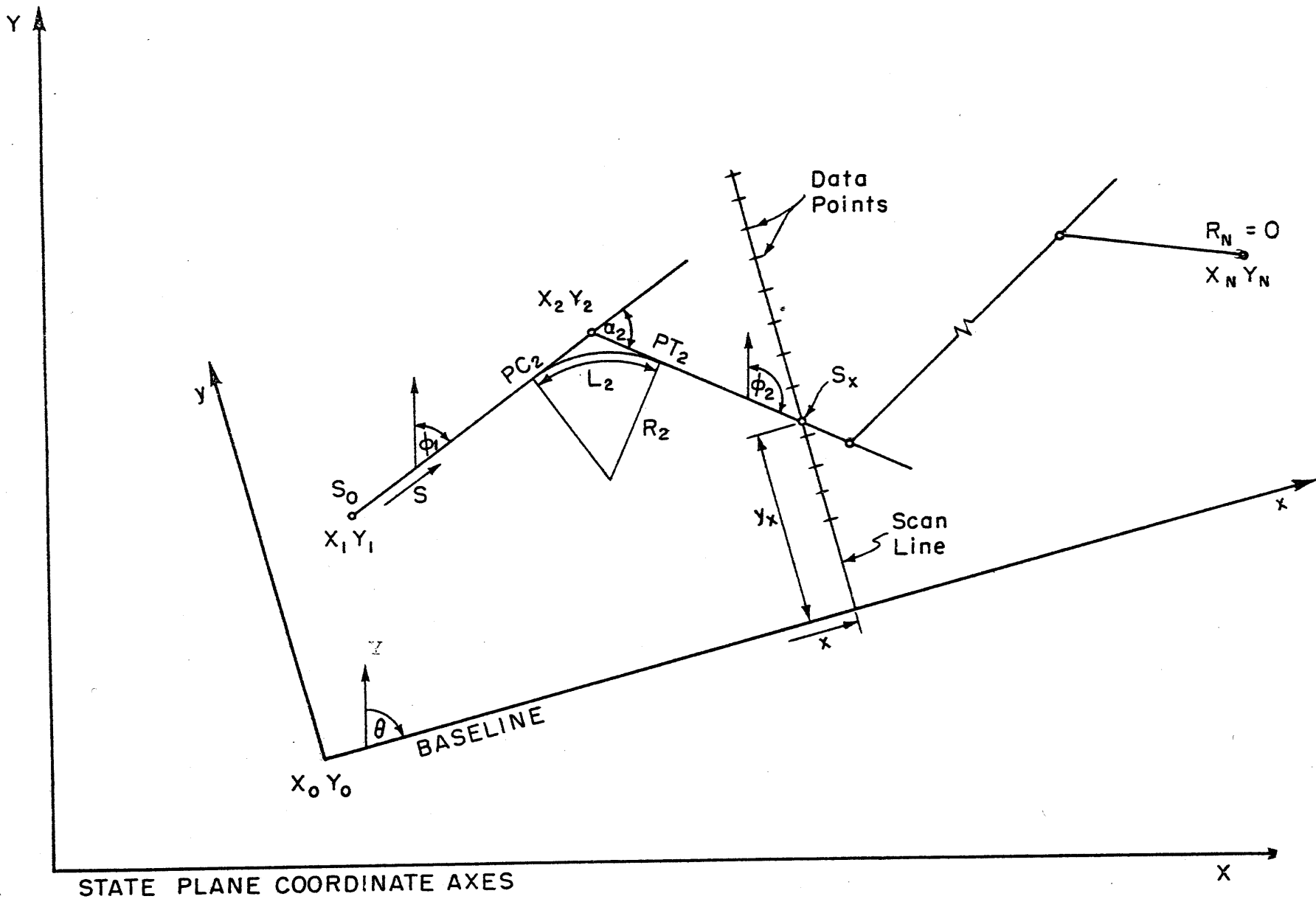
2. The azimuth of each tangent is computed, the curves computed, and the centerline stationed at each terrain section, P.C. and P.T.

3. The offset from the baseline to the centerline, the ground elevation, and the skew angle is computed for each terrain section.

DEFINITION OF TERMS

(See Figure 4-06:1)

- x_0, y_0 - State plane coordinates of the baseline origin
 θ - Azimuth, measured clockwise from North, of the baseline
 x, y - Baseline coordinates of a point
 S_0 - Centerline stationing of the origin of the alignment
 PI - Point of intersection of two alignment tangents
 x_i, y_i - State plane coordinates of PI_i
 R_i - Radius of circular curve associated with PI_i (curve i)
 L_i - Length of curve i
 T_i - Tangent length of curve i
 α_i - Angle of intersection of tangents at PI_i , measured clockwise from extended tangent to forward tangent
 PC_i - Point of curvature of curve i
 PT_i - Point of tangency of curve i
 ϕ_i - Azimuth, measured clockwise from North, of forward tangent of curve i
 S_p - Centerline stationing of any point P on the alignment
 S_x - Centerline stationing of the point of intersection of a cross section and the alignment
 y_x - Baseline y coordinate of the point of intersection of a cross section and the alignment
 z_x - Interpolated terrain elevation of the point of intersection of a cross section and the alignment
 ψ_x - Angle between the cross section and perpendicular to the alignment
 x_{max} - Baseline x coordinate of $X_N Y_N$ (terminus of the alignment)
 S'_{PI_i} - Centerline Station of PI_i along forward tangent.



STATE PLANE COORDINATE AXES

Fig. 4-06:1

MACRO BLOCK DIAGRAM

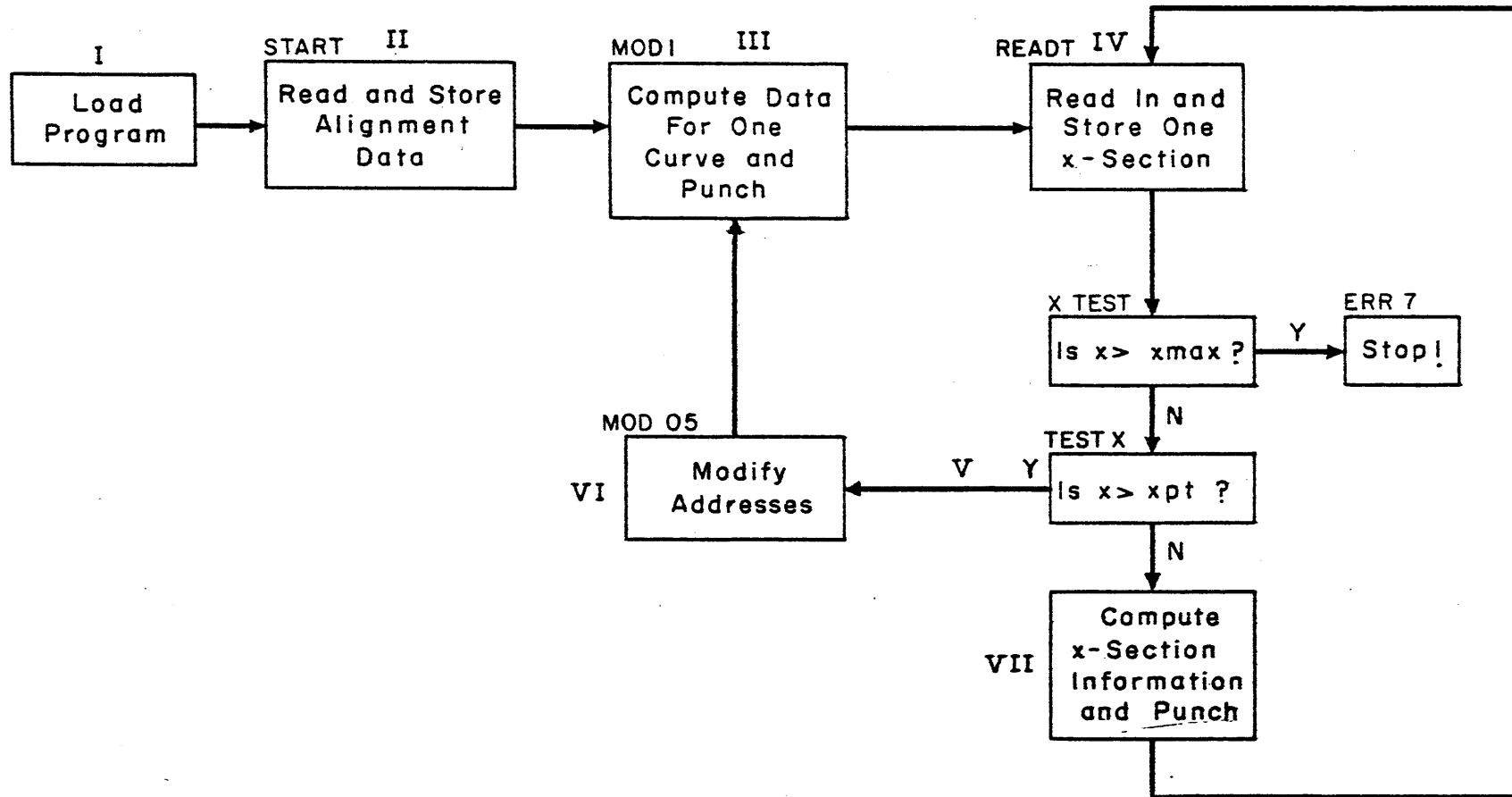


FIG. 4-06:2

GENERAL LOGIC OF HA-1

(See Fig. 4-06:2)

- Block I The program is loaded into storage
- Block II The Baseline Data Card and the Horizontal Alignment Definition Cards are read in and the data stored.
- Block III The data for the initial tangent and the first curve (S_{PC} , S_{PT} , L , T , θ) is computed, punched, and stored.
- Block IV The data for one cross section is read in and stored. The x-coordinate of this cross section is compared with the x value of the alignment terminus. If the cross section is beyond the terminus the program is completed and the computer stops.
- Block V The x value of the section is compared with the x coordinate of the PT (computed in Block III). If the cross section lies beyond the PT the data for the next curve is computed. If the cross section intersects the alignment before the PT the station of this intersection, its y offset and the terrain elevation can be computed.
- Block VI Prior to computing the data for a new curve the addresses of the instruction in Block III are modified.
- Block VII The data for the cross section (S_x , Y_x , Z_x and $\cos \psi_x$) is computed and punched. At this point control returns to Block IV where a new cross section is read in.

INPUT TO HA-1

The input is shown as it appears to the computer as opposed to the way it is punched on the cards

Baseline Data

This data is read in on a load card and defines the baseline with respect to the State Plane Coordinate System.

Word 1	IIIIIIIIII+	Identification
2	XXXXXXXX.XXX±	State Plane coordinates of
3	YYYYYYY.YYY±	baseline origin
4	AAA.AAAAAA+	The azimuth, in decimal degrees
		of the baseline, measured
		clockwise from State Plane North (Y)
5-10		Not used

Horizontal Alignment Definition Data

1 - Origin Data (First Card)

Word 1	IIIIIIIIII+	Identification
2	XXXXXXXX.XXX±	State Plane Coordinates
3	YYYYYYY.YYY±	of the Alignment Origin
4	SSSSSSS.SSS+	Centerline Station of the origin
5-10		Not used

2 - P.I. Data (As many cards as there are curves in the alignment)

Word 1	IIIIIIIIII+	Identification
2	XXXXXXXX.XXX±	State Plane Coordinates
3	YYYYYYY.YYY±	of P.I.'s
4	RRRRRRR.RRR+	Radius of Circular Curve
5-10		Not used

3 - Terminus Data (Last Card)

Word 1	IIIIIIIIII+	Identification
2	XXXXXXXX.XXX±	State Plane Coordinates
3	YYYYYYY.YYY±	of Alignment Terminus
4	000000000+	Identifies this as the terminus
		card
5-10		Not used

Terrain Data

The Terrain Data Cards (TDC) are composed of Beginning-of-Line Cards (BLC) and Data Cards. The data for one section is recorded on one BLC followed by one or more Data Cards. These are not load cards and are read in using Read Format C.

1 - Beginning-of-Line Cards

Word 1	0008999998+	The 8 in digit 7 indicates that this is a terrain data card. The 8 in digit 1 indicates that it is a BLC.
2	0000xxxxx.x+	Baseline x value of cross section
3-10		Not used

2 - Data Cards

Word 1	0008xxxxx9+	
Digit 1	9	Indicate Data Card (11 punch CC 12)
2	9	CC 13 Blank
	8	CC 13 11 or 12 punch
3	9	CC 30 Blank
	8	CC 30 11 or 12 punch
4	9	CC 47 Blank
	8	CC 47 11 or 12 punch
5	9	CC 64 Blank
	8	CC 64 11 or 12 punch
6	8	CC 13 (Succeeding Card) Blank
	9	CC 13 (Succeeding Card) 12 punch
7	8	Indicates Terrain Card
Word 2	0000xxxxx.x±	The x value of this section. The sign will be minus if there is an 11 punch in CC 13
3	YYYY.YZZZZ.Z±	The y-z coordinates of the first point on the card. The sign will be minus if there is an 11 punch in CC 30
4	YYYY.YZZZZ.Z±	The y-z coordinates of the second point on the card. The sign will be minus if there is an 11 punch in CC 47
5	YYYY.YZZZZ.Z±	The y-z coordinate of the third point on the card. The sign will be minus if there is an 11 punch in CC 64
6	YYYY.YZZZZ.Z±	The y-z coordinates of the fourth point on the card
7-10		Not used

OUTPUT OF HA-1

The output is shown as it is stored in the punch band rather than the way it is punched on the cards.

Curve Data

1 - Initial Tangent Card

Word 1	IIIIIIIIII+	Identification
2	AAA.AAAAAAA+	Azimuth of first tangent ahead (Decimal degrees)
3-9	000000000+	Not used
10	000000000+	Selects load card format

2 - Curve Definition Cards (one per P.I.)

Word 1	IIIIIIIIII+	Identification
2	AAA.AAAAAAA+	Azimuth of tangent ahead
3	SSSSSS.SSS+	Station of PC
4	SSSSSS.SSS+	Station of PT
5	TTTTTTT.TTT+	Curve Tangent Distance
6	AAA.AAAAAAA+	Deflection angle of curve measured clockwise from extended tangent to forward tangent
7	YYYYYYY.YYY+	Baseline y-coordinate of PC
8	SSSSSS.SSS+	Station of PI (along back tangent)
9	000000000-	Not used
10	000000000+	Selects load card format

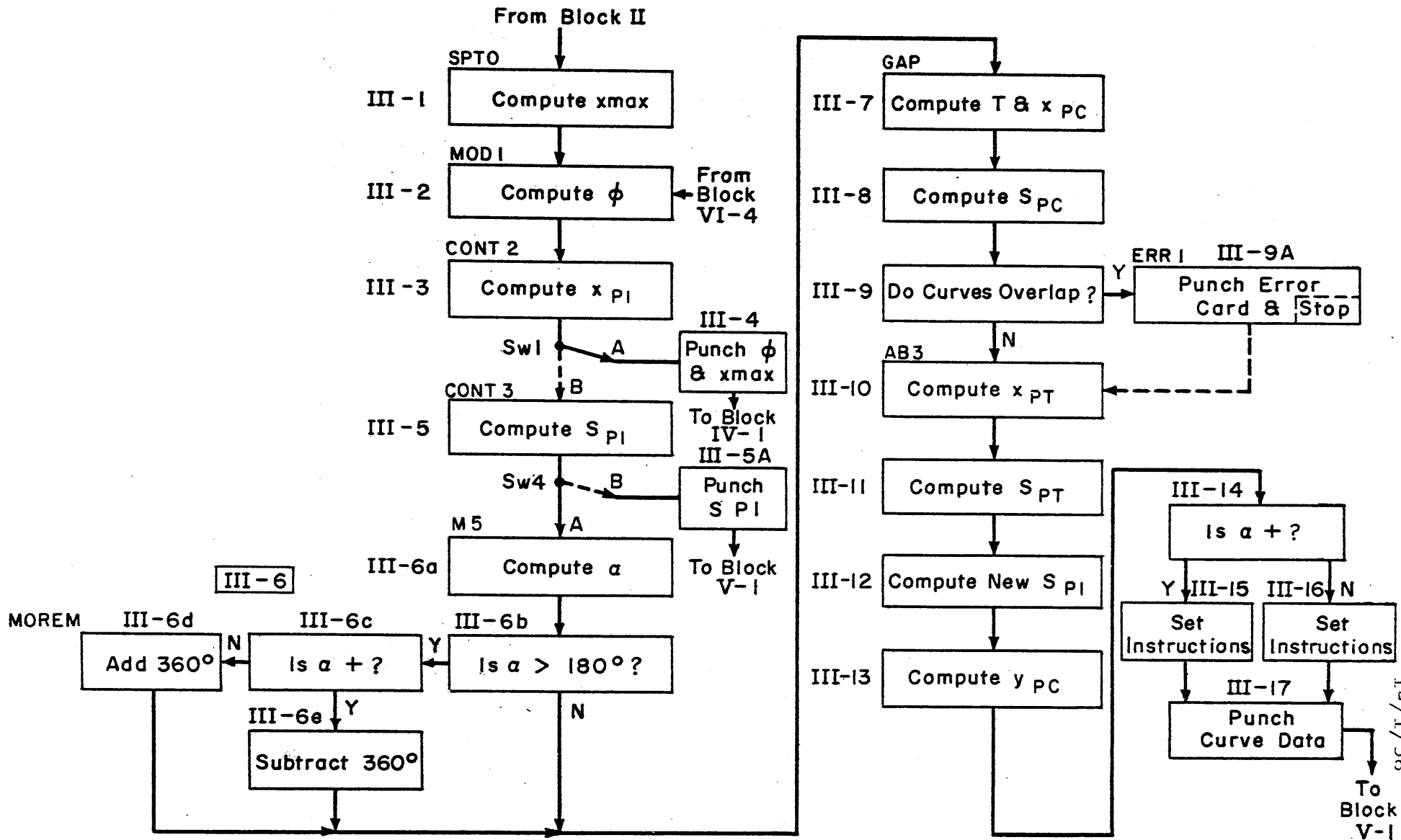
3 - Final Tangent Card

Word 1	IIIIIIIIII+	Identification
2-6	000000000+	Not used
7	xxxxxxx.xxx+	Baseline x coordinate of alignment terminus
8	SSSSSS.SSS+	Station of alignment terminus
9	000000000-	Not used
10	000000000+	Selects load card format

CROSS SECTION DATA (ONE PER CROSS SECTION)

Word 1	IIIIIIIIII+	Identification
2	xxxxxxx.xxx+	Baseline x-coordinate of section
3	SSSSSS.SSS+	Station of centerline intersection
4	YYYYYYY.YYY+	Baseline y-coordinate of centerline intersection
5	zzzzzzz.zzz+	Ground elevation at centerline
6	000000000+	Not used
7	C.CCCCCCCC±	Cosine of skew angle (ψ) of section
8,9	000000000-	Not used
10	0080000080	Selects Punch Format B

BLOCK III



MIT - MDPW - RPR DTM MANUAL

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Fig. 4-06:3

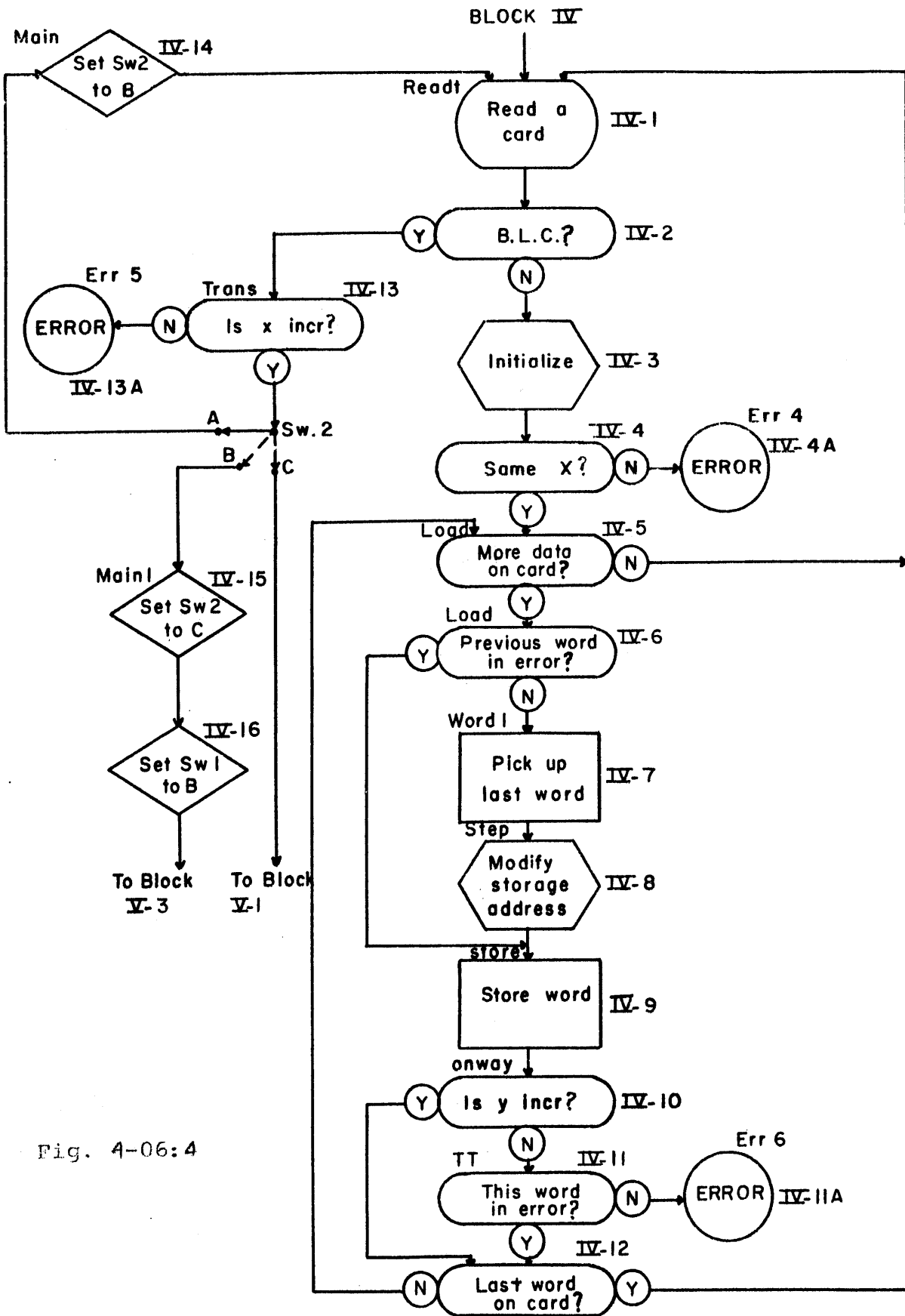
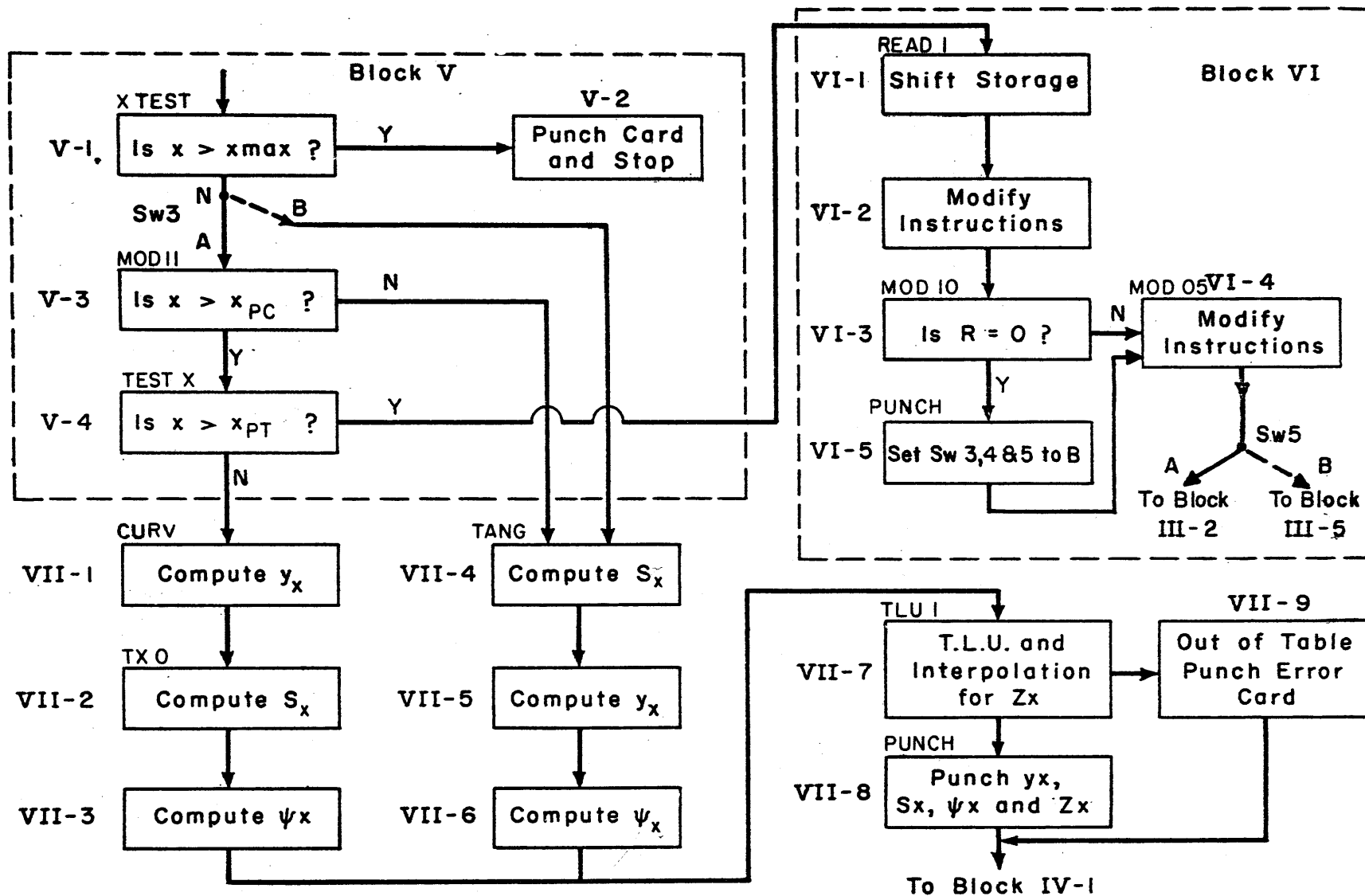


Fig. 4-06:4

BLOCK V, VI AND VII



MIT - MDPW - BPR

DTM MANUAL

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Fig. 4-06:5

SUBROUTINES

1 - Sin A, Cos A, (A in radians)

Source: IBM 650 General Library #3.1.010

Range: Sin A: $-7.2 \leq A \leq + 7.2$ Cos A: $-8.8 \leq A \leq + 8.4$

Running Time: 123 ms.

Method: 12th power in Taylor Series: IBM 650
Technical Newsletter #9, p. 34.

Accuracy: Maximum Error 0.000000003

2 - Square Root A

Source: IBM 650 General Library #3.1.002

Range: $0 \leq A \leq 0.9999999989$

Running Time: For random A 120 ms.

Method: Newton's

Accuracy: Maximum error: 0.0000000003

3 - Arc sin A

Source: IBM 650 General Library #3.1.012

Range: $0 \leq A \leq 1$

Running Time: For random A: 200 ms.

Method: Polynomial Approximation: Hasting, p. 163

Accuracy: Maximum error: 0.000000005

RESTRICTIONS

- 1 - Alignment Definition The alignment is defined by a number of points, defining the tangents, and the radii of the circular curves connecting the tangents.
- a. Therefore, the minimum number of points needed to define an alignment is two.
 - b. The origin and terminus (first and last points) must be on a tangent section, e.g. PC, PT, PI. They may not be on a curve.
 - c. Due to storage limitations the maximum number of points allowable is 50. This defines an alignment with 48 curves.
 - d. The circular curves joining the tangents must not overlap, i.e., $S_{PC_{i+1}}$ must be greater than or

equal to S_{PT_1}

- e. The radius of any curve cannot be less than 0.001 feet.

2 - Terrain Data

- a. The x value on the data card must agree with the x value on the preceding Beginning-of-Line card
- b. The cross sections must be in order of increasing x
- c. The data points must be in order of increasing y.

SCALING AND SIGNIFICANT DIGITS

Distances and elevations are used with and computed to three decimal places. Sines and cosines are computed to nine decimal places. Tangents are computed to eight decimal places. Angles are used in radian form to nine decimal places and are converted to decimal degrees with seven decimal places.

The arcsin of θ is computed using ΔX and ΔY . In order to allow long tangent sections (up to 20 miles between P.I.'s) the Δ 's are taken to the nearest foot. When the distance between P.I.'s is very short (100 feet or less) the accuracy of the computed azimuth will be in the order of 1 or 2 minutes. This can be avoided by using double precision but this was not deemed advisable.

MATHEMATICAL ANALYSISHorizontal Geometry*

(See Fig. 4-06:a)

$$\phi_1 = \tan^{-1} \frac{x_2 - x_1}{y_2 - y_1} = \sin^{-1} \frac{x_2 - x_1}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}$$

$$\alpha = \theta_2 - \theta_1$$

$$T_2 = R_2 \tan \left(\frac{\alpha}{2} \right)$$

$$L_2 = R_2 \alpha_2$$

$$S_{PC_2} = S_{PI_2} - T_2$$

$$S_{PT_2} = S_{PC_2} + L_2$$

Coordinate Computations**

(See Fig. 4-06:6b)

Given: $x_0, y_0, x_1, y_1, x_2, \theta_1, x, T_2, x_c, \alpha$

$$x_{PI_2} = (x_{PI_2} - x_0) \sin \theta + (y_{PI_2} - y_1) \cos \theta$$

$$S_{PI_2} = S_{PI_1} + \frac{x_{PI_2} - x_{PI_1}}{\cos(\theta - \phi_1)}$$

$$x_{PC_2} = x_{PI_2} - T_2 \cos(\theta - \phi_1)$$

$$y_{PC_2} = (x_0 - x_1) \cos \theta - (y_0 - y_1) \sin \theta + (x_{PC_2} - x_{PI_1}) \tan(\theta - \phi_1)$$

$$S_x = S'_{PT_1} + \frac{x - x_{PI_1}}{\cos(\theta - \phi_1)}$$

$$\text{where } S'_{PI_1} = S_{PT_1} - T_1$$

*Route Location and Surveying - T. F. Hickerson, McGraw-Hill
or any Route Surveying Text.

$$y_x = (Y_1 - Y_0) \sin\theta - (X_1 - X_0) \cos\theta \\ + (x - x_{PI_1}) \tan(\theta - \phi_1)$$

$$\psi_x = (\theta - \phi_1)$$

$$y_c = y_0 + \sqrt{R_2^2 - (x_c - x_0)^2} \quad (\alpha_2 \text{ positive})$$

$$y_c = y_0 - \sqrt{R_2^2 - (x_c - x_0)^2} \quad (\alpha_2 \text{ negative})$$

where x_0 and y_0 are the baseline coordinates of the origin of the circular curve

$$x_0 = y_{PC_2} + R_2 \sin(\theta - \phi_1) \quad (\alpha_2 \text{ positive})$$

$$x_0 = y_{PC_2} - R_2 \sin(\theta - \phi_1) \quad (\alpha_2 \text{ negative})$$

$$y_0 = y_{PC_2} - R_2 \cos(\theta - \phi_2) \quad (\alpha_2 \text{ positive})$$

$$y_0 = y_{PC_2} + R_2 \cos(\theta - \phi_2) \quad (\alpha_2 \text{ negative})$$

$$s_c = s_{PC_2} + R_2 B$$

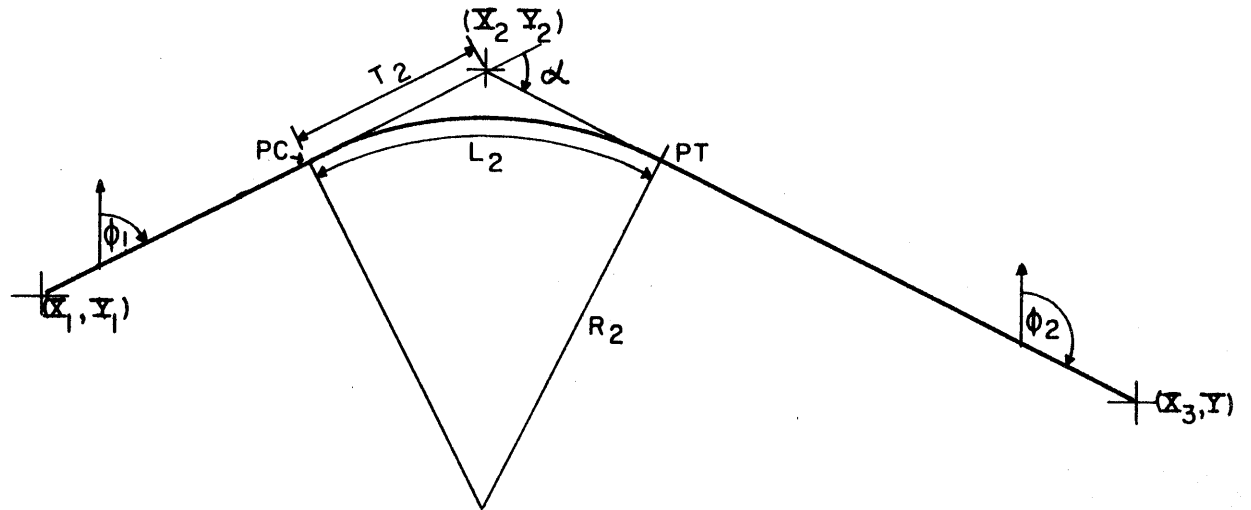
$$\text{where: } B = 2 \left(\frac{B}{2} \right) = 2 \left[\sin^{-1} \left(\frac{C/2}{R_2} \right) \right]$$

$$\text{and } c = \sqrt{(x_c - x_{PC_2})^2 + (y_c - y_{PC_2})^2}$$

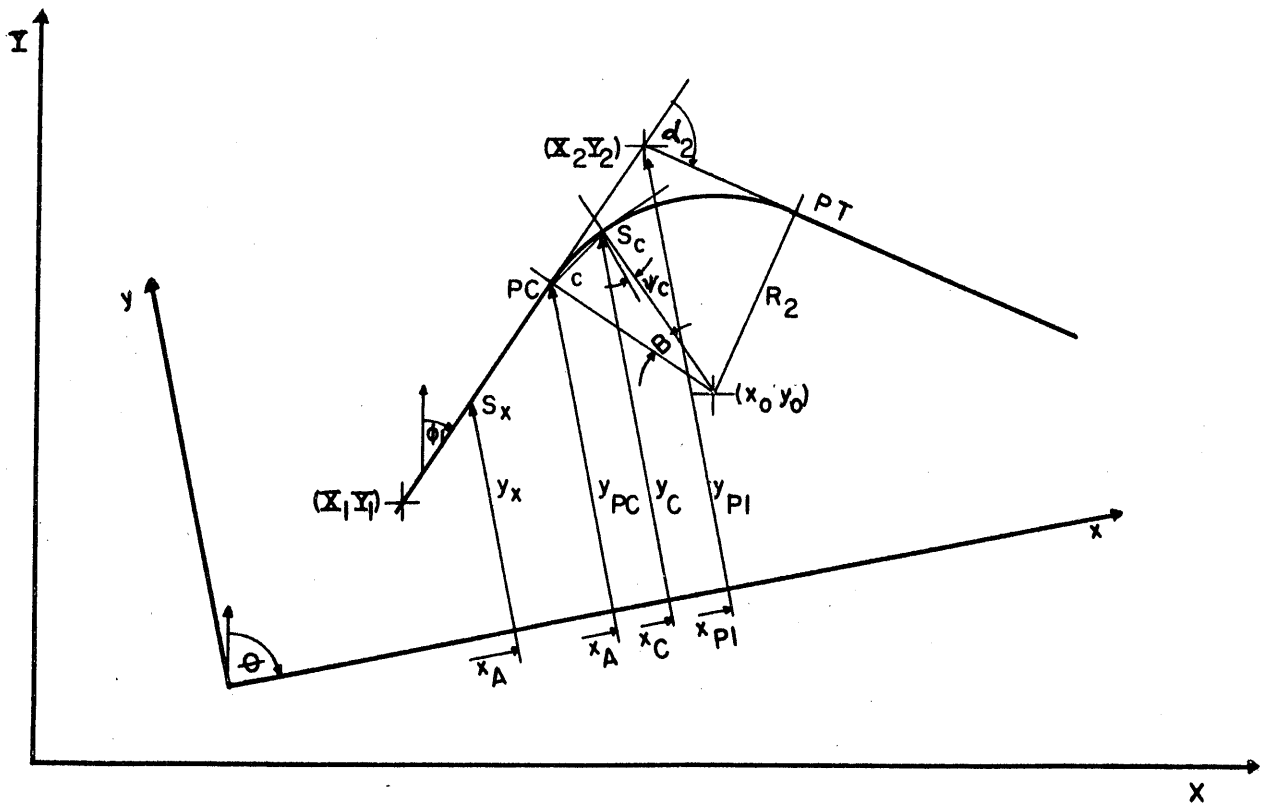
$$\psi_c = \theta - (\phi_1 + B) \quad (\alpha \text{ positive})$$

$$= \theta + (\phi_1 - B) \quad (\alpha \text{ negative})$$

***"Analysis of Highway Geometrics and Design Data Input For an Integrated Photogrammetric-Electronic Computer System".
R. A. Laflamme, B. S. Thesis, MIT, 1957 (Unpublished)



(a)



(b)

Fig 4-06:6

DTM EVEN STATION INTERPOLATION PROGRAM HA-2PROGRAM ANALYSISProgram Description And Engineering Procedure

1. The output of HA-1 gives the interpolated ground elevation on the centerline at each terrain cross-section and the centerline station of the cross-section. Usually these will be odd stations which would be inconvenient to use in plotting a terrain profile of the centerline.

2. The HA-2 program takes the output of HA-1 and interpolates terrain elevations at even centerline stations. The output is therefore a series of ground elevations at even stations to be used for plotting a ground profile. The plotted ground profile is used in selecting trial grade lines for each trial alignment.

DEFINITION OF TERMS

- S - Centerline station of point whose elevation is desired
S₁ - Centerline station of first point to be used in interpolation
S₂ - Centerline station of second point to be used in interpolation
S₂ > S₁
Z₁ - Terrain elevation of point S₁
Z₂ - Terrain elevation of point S₂
S₀ - First even station
Δ - Increment between even stations
S_x - Centerline station of any terrain section (from HA-1 output)
Z_x - Terrain elevation at S_x

INPUT TO HA-2

The input is shown as it appears to the computer, rather than the way it is punched on the cards

HA-2 Data (Load Card)

Word 1		Not used
2	SSSSSS.SSS+	S_0 , First even station desired
3	DDDDDD.DDD+	Δ , Increment between even stations
4		Not used

Cross-Section Specification Data (HA-1 Output)

Word 1,2		Not used
3	OSSSSS.SSS+	Centerline station of section
4		Not used
5	000ZZZ.ZZZ+	Terrain elevation at centerline
6-9		Not used
10	IIIIIIIIII+	Identification

OUTPUT OF HA-2

The output is shown as it is stored in the punch band rather than the way it is punched on the card.

Even Station Data (One card per station)

Word 1	IIIIIIIIII+	Identification
2	000000000+	Not used
3	OSSSSS.SSS+	Even centerline station
4	000000000+	Not used
5	000ZZZ.ZZZ+	Interpolated ground elevation
6-9	000000000+	Not used
10	008000080+	Selects Punch Format B

HA2 BLOCK DIAGRAM

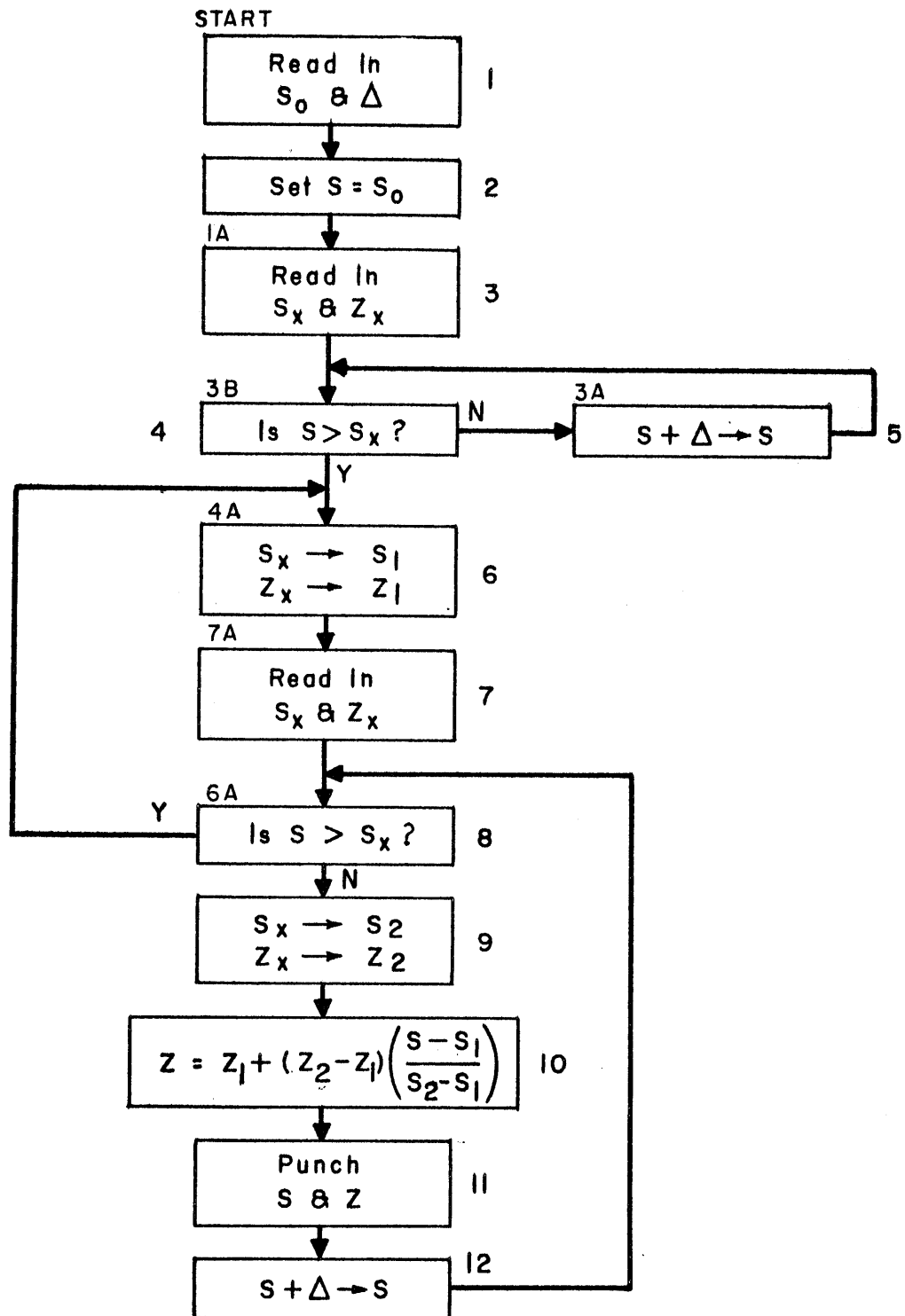


Fig. 4-16:1

SCALING AND SIGNIFICANT DIGITS

Same as HA-1

SUBROUTINES USED

None

RESTRICTIONS

- The value of Δ must be positive (the elevation must be increased in order of increasing S)

MATHEMATICAL ANALYSIS

Standard linear interpolation is used.

SYMBOLS USED FOR TEMPORARY STORAGE

Q S, station whose elevation is desired

Con Δ , increment between even stations

S_1, Z_1 } Station and elevation of points

S_2, Z_2 } bracketing desired point

DTM PARALLEL OFFSET ALIGNMENT PROGRAM HA-3PROGRAM ANALYSISProgram Description & Engineering Procedure

1. As an aid in selecting the grade line, for considering lateral shifts of the alignment, and for other types of studies, it will often be of value to have terrain profiles for offset lines parallel to the centerline.

2. The HA-3 program is the same as the HA-1 program except that, in addition to the HA-1 output data for the centerline, a similar set of data is obtained for a right and a left parallel offset line.

3. The data for the parallel offset lines may also be put through HA-2 for even station interpolation of profile plot data after sorting the cards for the three separate lines.

4. All specifications and procedures described under HA-1 are applicable to HA-3.

5. HA-3 is particularly useful when a separate grade line is being considered for each half of a divided highway. The output of HA-3 can also be used as the input to a rapid reconnaissance type earthwork program for considering a very large number of alternate lines in the early stages.

DEFINITION OF TERMS

Same as HA-1 plus:

LOS: Perpendicular distance from centerline to left offset line
 ROS: Perpendicular distance from centerline to right offset line
 Y_1 : Baseline y coordinate of the intersection of the left offset line and a terrain cross-section
 Y_r : Baseline y coordinate of the intersection of the right offset line and a terrain cross-section
 Z_1 : Elevation of intersection of left offset line and a terrain cross-section
 Z_r : Elevation of intersection of right offset line and a terrain cross-section

Right-Left: Right and left are referenced to a person facing in the direction of increasing centerline stationing.

INPUT TO HA-3

The input is shown as it appears to the computer, rather than the way it is punched on the cards.

The input data to this program includes all the input data to HA-1 plus the HA-3 data card.

Word 1		Not used
2	LLLLLLL.LLL±	Left offset distance
3	RRRRRRR.RRR±	Right offset distance
4-9		Not used
10	IIIIIII.III±	Identification

OUTPUT OF HA-3

The output of HA-3 includes all the output of HA-1 and has two additional cards per cross-section, one for the left offset point and one for the right offset point.

These two additional cards have the same Identification, x , S , and $\cos \psi$ as the centerline card. In addition to this they have their proper y -coordinate and terrain elevation.

BLOCK VIII

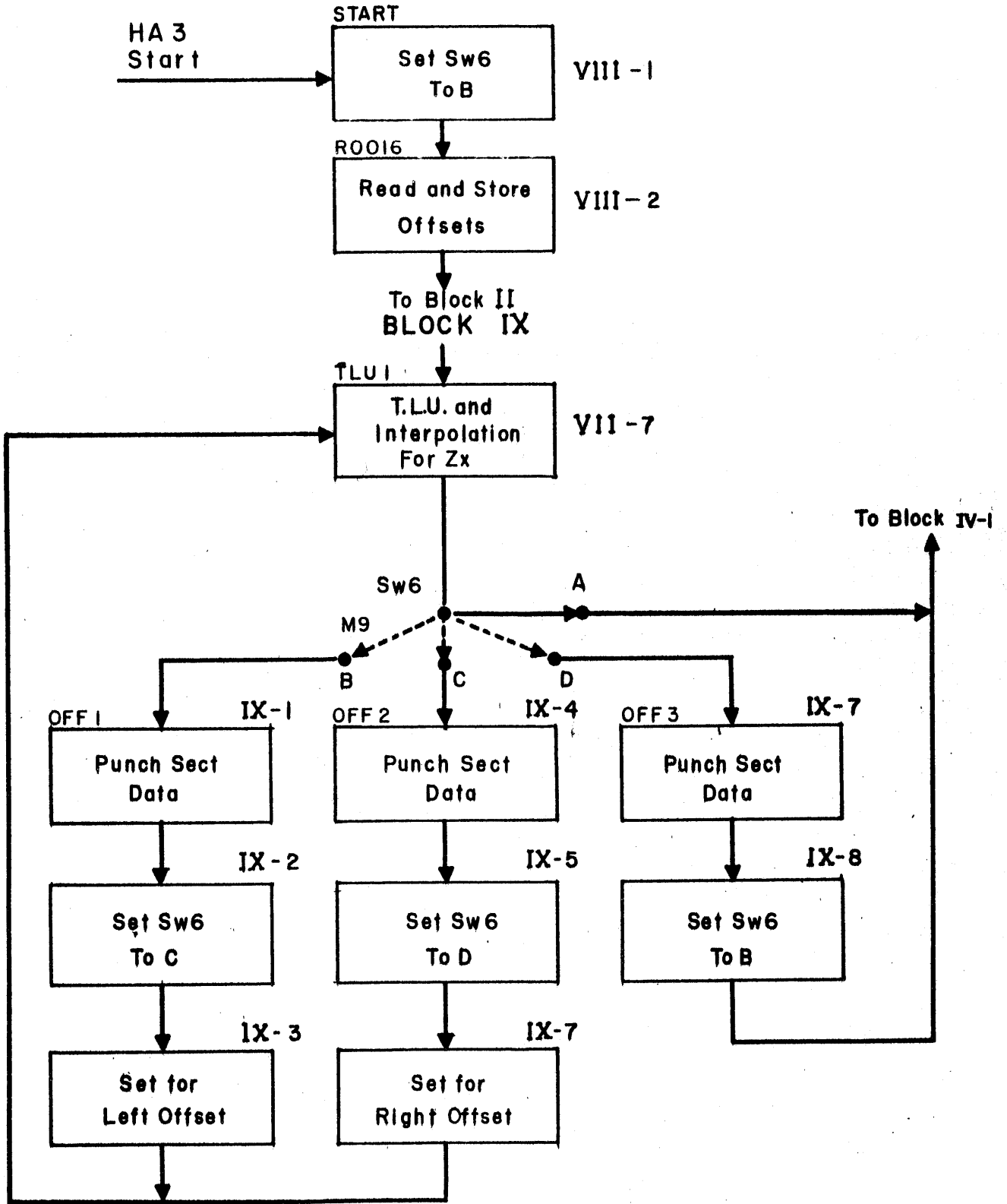


FIG. 4-26:1

SUBROUTINES

Same as HA-1.

RESTRICTIONS

The restrictions for HA-3 are the same as for HA-1 with the addition that LOS and ROS may each range from -9999.999 to +9999.999. They would ordinarily be on opposite sides of the centerline but will be on the same side when either the LOS or the ROS is negative.

ACCURACY AND SIGNIFICANT DIGITS

Same as HA-1.

MATHEMATICAL ANALYSIS

Same as HA-1.

SYMBOLS USED FOR TEMPORARY STORAGE

Same as HA-1 plus:

DELL - LOS left offset distance

DELR - ROS right offset distance

SPECIAL ALIGNMENT GEOMETRY PROGRAM HA-4PROGRAM ANALYSISProgram Description and Engineering Procedure

1. The HA-4 program is a special version of the HA-1 program for computing alignment geometry only. The DTM terrain data deck is not used.
2. The HA-4 program may be used to compute the curve data and to station the centerline of any alignment or other line defined by P.I. coordinates and curve radii. The program may be used in conjunction with a traverse program if the line is defined by tangents and bearings.
3. Since no cross-sections are involved, the absence of the requirement that the sections be in order of increasing x value means that the alignment may double back on itself or loop internally. Therefore, HA-4 may be used to compute the geometry of interchanges and ramps. However, the HA-1 specification that curves may not overlap holds also for HA-4.

DEFINITION OF TERMS

Same as HA-1

INPUT TO HA-4

Same Baseline and Alignment Definition data as HA-1. No terrain data is used. The X and Y coordinate of the Baseline origin are equal to zero and the azimuth of the baseline is equal to ninety degrees.

OUTPUT OF HA-4

Same curve definition data as HA-1. Since no terrain data is used as input the output does not include any cross-section data.

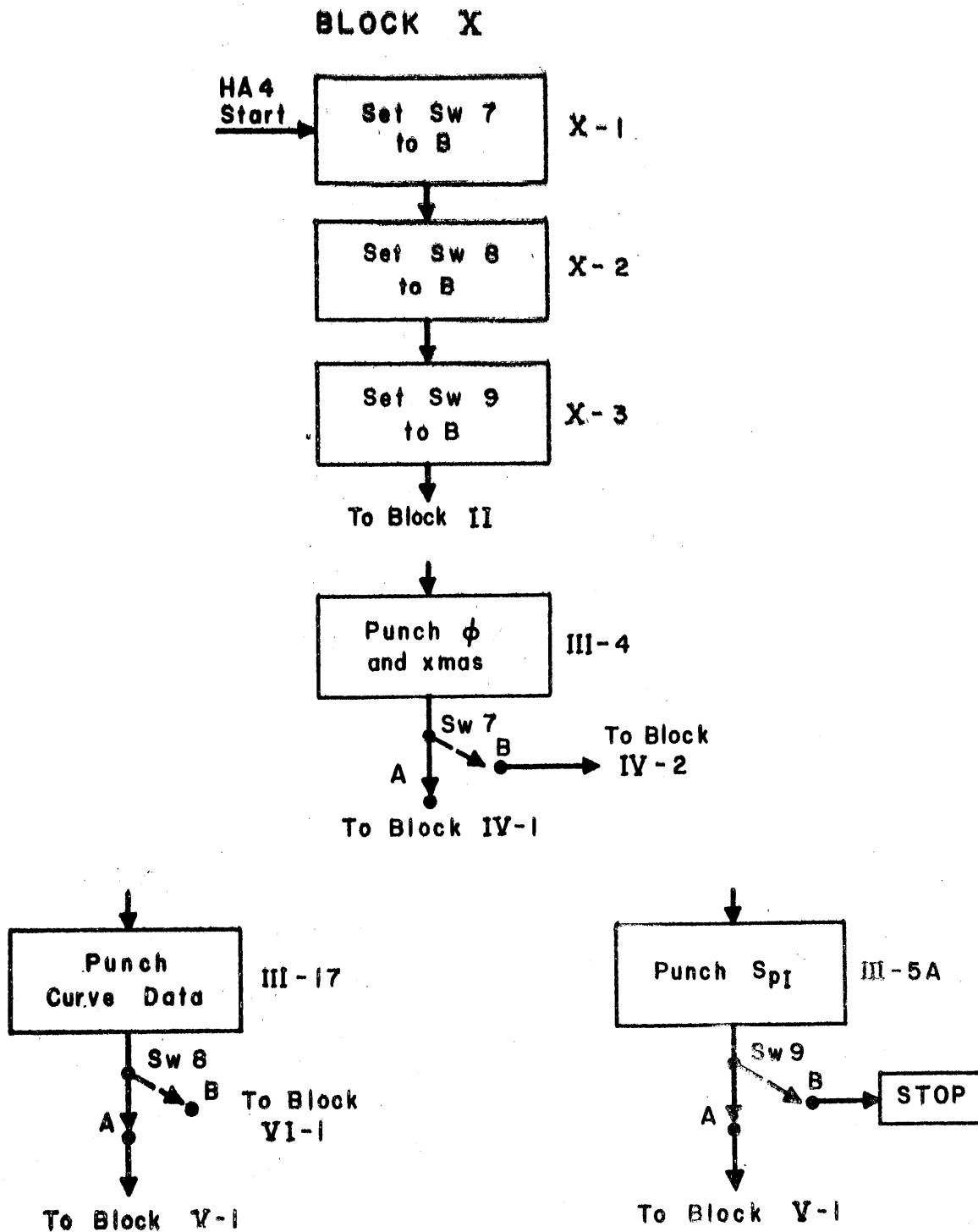


Fig. 4-36:1

BLOCK DESCRIPTION

(See Fig. 4-36: 1)

The HA-4 program is an option of the HA-1 program. The HA-1 program can be divided into two main parts: computation of alignment data and computation of cross-section data. HA-4 uses only the section which computes the alignment data.

Block X is used to set switches 7, 8, and 9 to B. The switches are used to by-pass all computations involving terrain data.

SCALING AND SIGNIFICANT DIGITS

Same as HA-1

RESTRICTIONS

Same as HA-1 (Except for terrain data)

SUBROUTINES

Same as HA-1

MATHEMATICAL ANALYSIS

Same as HA-1

APPENDIX C

Program Analysis of DTM Vertical Alignment Programs VA-1 and VA-2. The programs are examples of a basic DTM vertical alignment program and a general purpose version of it.

DTM BASIC VERTICAL ALIGNMENT PROGRAM VA-1GENERAL DESCRIPTIONEngineering Procedure

1. With the aid of the terrain profiles plotted from the output of HA-1 or HA-2 and other grade line selection data, the engineer selects the trial grade lines to be numerically evaluated for each horizontal alignment as in standard procedure.
2. The centerline station and elevation of each VPI, the origin, and the terminus of the profile are taken from the profile plot. The length of the vertical curve at each VPI is designated by the engineer.
3. If the profile grade reference point on the highway cross section is above or below the centerline grade reference point, as is often the case on divided highways, the elevation difference between these two points is also furnished by the engineer.

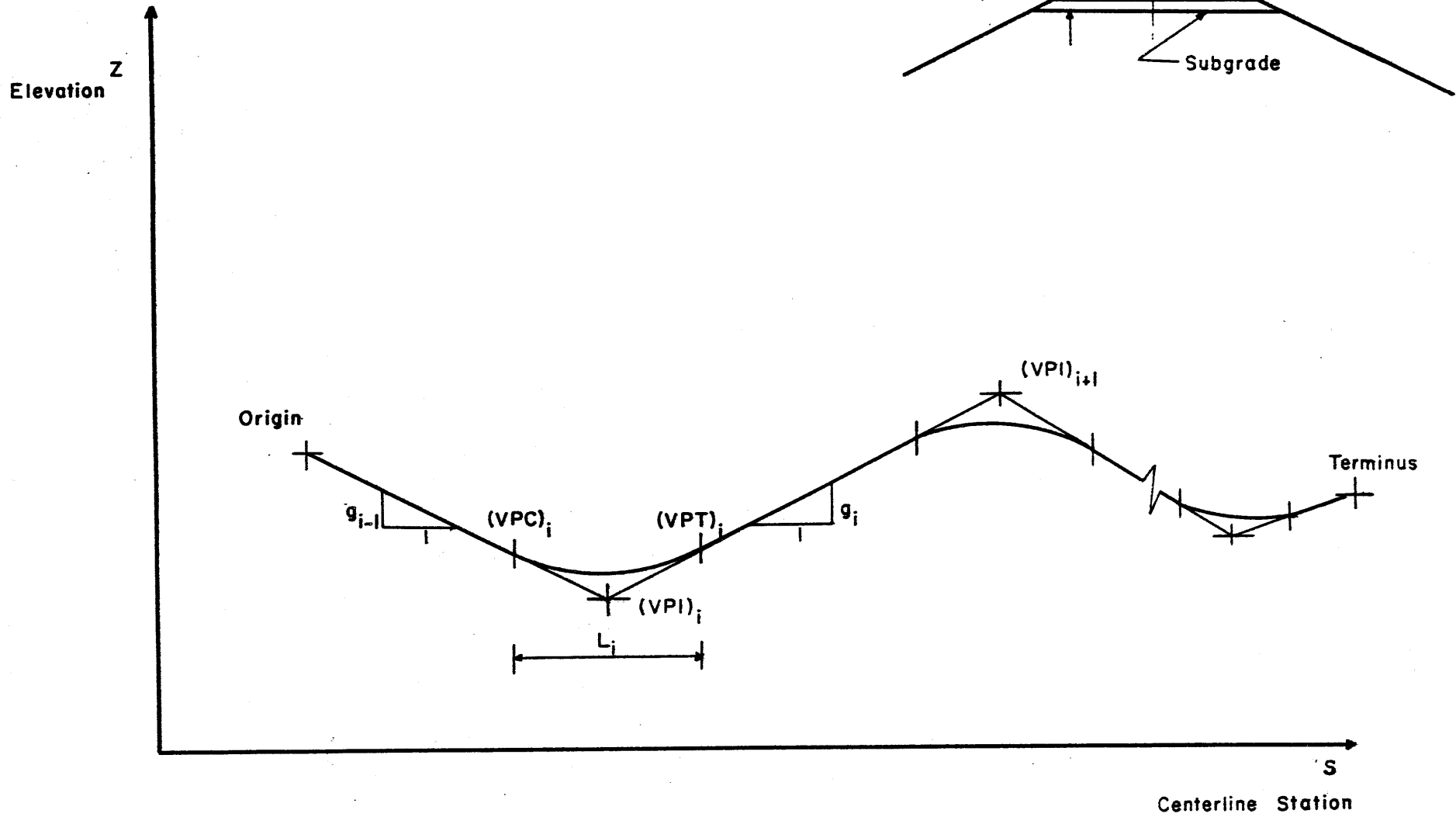
Program Description

1. The purpose of the VA-1 program is to compute the geometry of the vertical alignment.
2. For each VPI, the grade of the tangent ahead and the station and profile elevation of VPC and VPT are computed.
3. The profile elevation of the centerline at each terrain cross section is computed and combined with the output of HA-1 to present a complete horizontal and vertical definition of the alignment for each terrain cross section.

DEFINITION OF TERMS

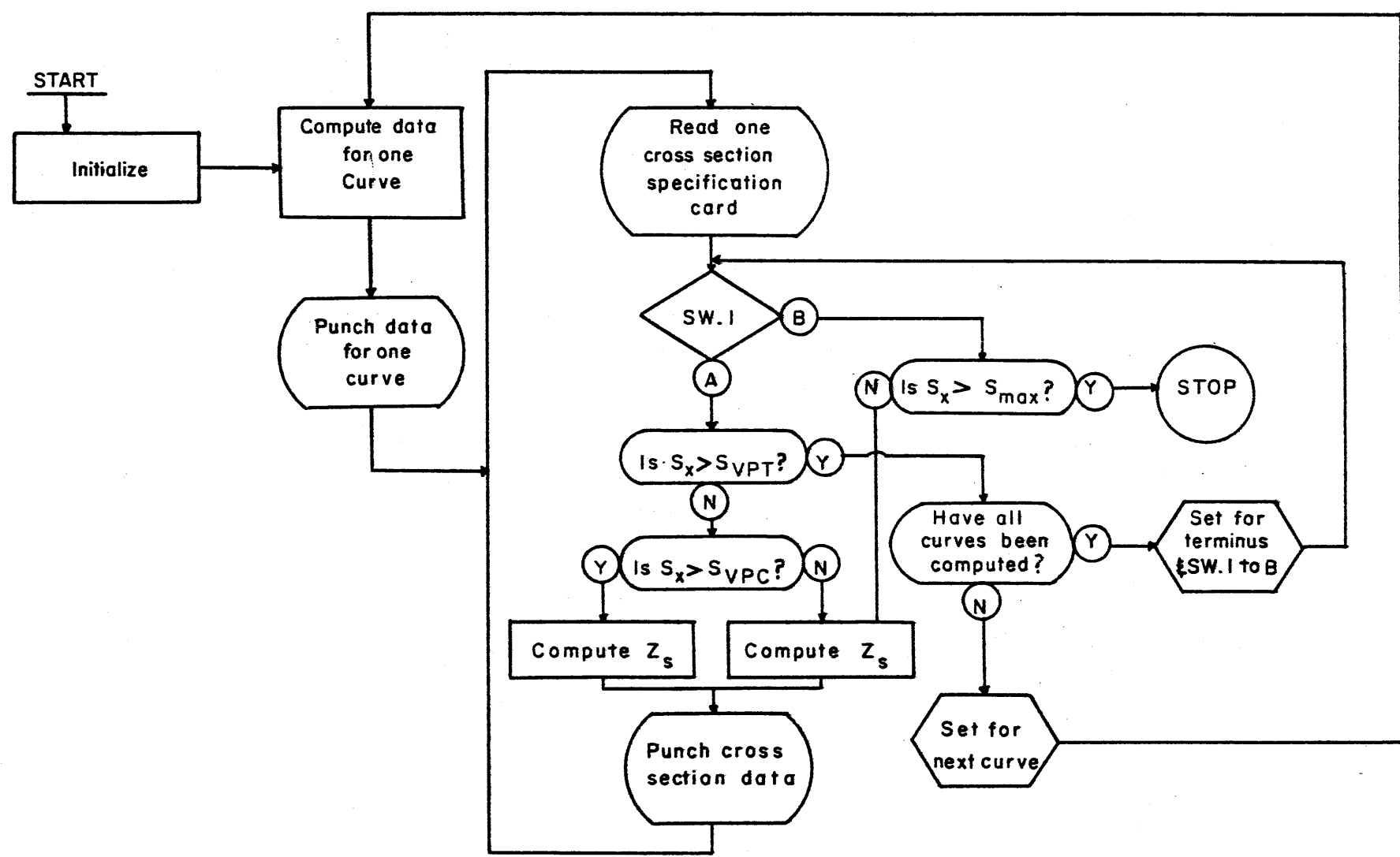
(See Fig. 6-06:1)

S_i	Centerline stationing of point j
Z_i	Elevation of point j
d	Profile - Subgrade Difference
PI_i	Vertical point of intersection at vertical curve i. Point of intersection of two grades, g_{i-1} g_i
S_i	Centerline station of PI_i
Z_i	Profile elevation of PI_i
L_i	Length of vertical curve i
x	Baseline x-coordinate of any cross section
y	Baseline y-coordinate of any point
Z_e	Ground elevation at intersection of a particular x-section and alignment
Z_s	Profile elevation at intersection of x-section and alignment
$\cos\psi_x$	Cosine of ψ , the skew angle of cross section x
g_i	Grade of vertical tangent
S_{PC_i}	Centerline station of vertical point of curvature (VPC) of curve i
Z_{PC_i}	Profile elevation of VPC _i
S_{PT_i}	Centerline station of vertical point of tangency (VPT) of curve i
Z_{PT_i}	Profile elevation of VPT _i
S_x	Centerline station of intersection of cross section ψ and the alignment
S_{max}	Centerline station of terminus.



NOTATION USED IN DTM VERTICAL
ALIGNMENT PROGRAMS VA-1 and VA-2

Figure 6-06:1



GENERAL LOGIC OF VA-1

Fig. 6-06:2

GENERAL LOGIC OF VA-1

(See Fig. 6-06:2)

After the program is initialized, i.e., all addresses and switches are reset, the first grade and the parameters associated with the first curve (S_{VPC} , S_{VPT} , Z_{VPC} , Z_{VPT} , and g) are computed. This curve data is then punched and a cross section specification card is read in.

Switch 1 is a logical switch and will remain in position "A" until the parameters for the last curve have been computed. Therefore, after a card has been read in the next step will normally be to compare the S_x value from the card with the centerline station of the VPT (S_{VPT}) just computed.

If S_x is not greater than S_{VPT} S_x is compared with the centerline station of the VPC just computed (S_{VPC}). If S_x is less than S_{VPC} the cross section intersects the grade before the vertical curve. Z_s is then computed and is added to the data read in on the cross section specification card and all this data is punched.

If S_x is greater than S_{VPT} the cross section intersects the alignment on the forward grade. A test is therefore made to determine if the data for all curves has been computed. If the data for all curves has been computed Switch 1 is set to B and control goes to the switch. All succeeding values of S_x will be tested against S_{max} , the station of the terminus. If S_x is less than the terminus the cross section intersects the alignment on the last grade and Z_s is computed.

If S_x is greater than S_{max} the program is terminated.

If all curves have not been computed the necessary instructions are modified and another set of curve data is computed.

INPUT TO VA-1

The input is shown as it appears to the computer, rather than the way it is punched on the cards:

Profile-Subgrade Difference (d)

This factor is not read in under program control but is loaded prior to the start of the program. If no value is loaded it is assumed to be zero, but any value loaded will remain until it is changed.

Scaling

ddddddd.dddt

Alignment Definition Data

This data defines the vertical alignment and is read in on load cards under program control.

Word 1	IIIIIIIIII+	Identification
Word 2	SSSSSS.SSS+	Station of origin, each VPI and terminus
Word 3	LLLLLLL.LLL+	Vertical curve length at each VPI. On the terminus card L must equal zero since this is used for a test.
Word 4, 5, 6		Not used

Cross Section Specification Data (HA-1 output)

Word 1	0009000000+	The "9" is used to identify this card format
Word 2	xxxxxxx.xxx+	Baseline x-coordinate of section
Word 3	0SSSSSS.SSS+	Centerline station of section
Word 4	000yyyy.yyy+	Baseline y-coordinate of centerline-cross section intersection
Word 5	000ZZZZ.ZZZ+	Terrain elevation at centerline
Word 6	Blank	Not used
Word 7	c.ccccccccc±	Cosine of ψ the skew angle
Word 8	0000000000+	Not used
Word 9	0000000000+	Not used
Word 10	IIIIIIIIII+	Identification

OUTPUT OF VA-1

The output is shown as it is stored in the punch band rather than the way it is punched on the cards.

1 - Vertical Curve Data

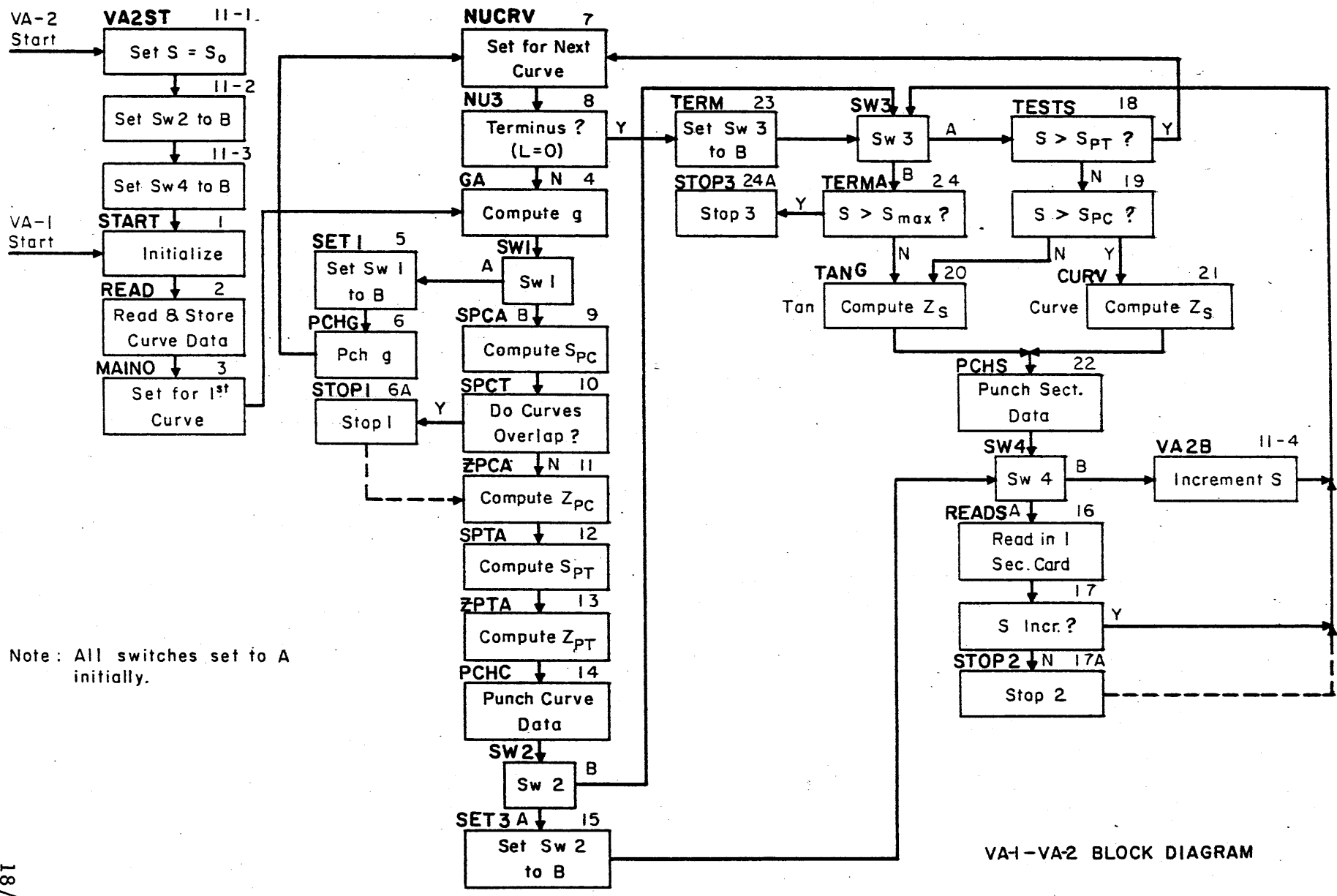
Word 1	IIIIIIIIII+	Identification
Word 2	.GGGGGGGGG±	Grade ahead
Word 3	SSSSSSS.SSS+	Station of VPC
Word 4	ZZZZZZZ.ZZZ±	Elevation of VPC
Word 5	SSSSSSS.SSS+	Station of VPT
Word 6	ZZZZZZZ.ZZZ±	Elevation of VPT
Word 7,8,9	000000000-	Not used
Word 10	000000000+	Selects load card format

2 - Cross Section Definition Data

Word 1	IIIIIIIIII+	Identification
Word 2	xxxxxxx.xxx+	Baseline x-coordinate of cross section
Word 3	0SSSSSS.SSS+	Centerline station of cross section
Word 4	oooyyyy.yyy	Baseline y-coordinate of centerline-cross section intersection
Word 5	000zzzz.zzz±	Terrain elevation at centerline
Word 6	000zzzz.zzz±	Profile elevation for this cross section
Word 7	c.cccccccc±	Cosine of skew angle
Word 8,9	000000000-	Not used
Word 10	0080000080+	Selects Punch Format B

3 - Alphabetic Error Cards

Words 1-6	AAAAAAAAAA+	Alphabetic codes
7-8	xxxxxxxxxx±	Numerical information associated with error stop
9	000000000-	Not used
10	000000008+	Indicates alphabetic information



Note: All switches set to A initially.

VA1-VA2 BLOCK DIAGRAM

SCALING AND SIGNIFICANT DIGITS

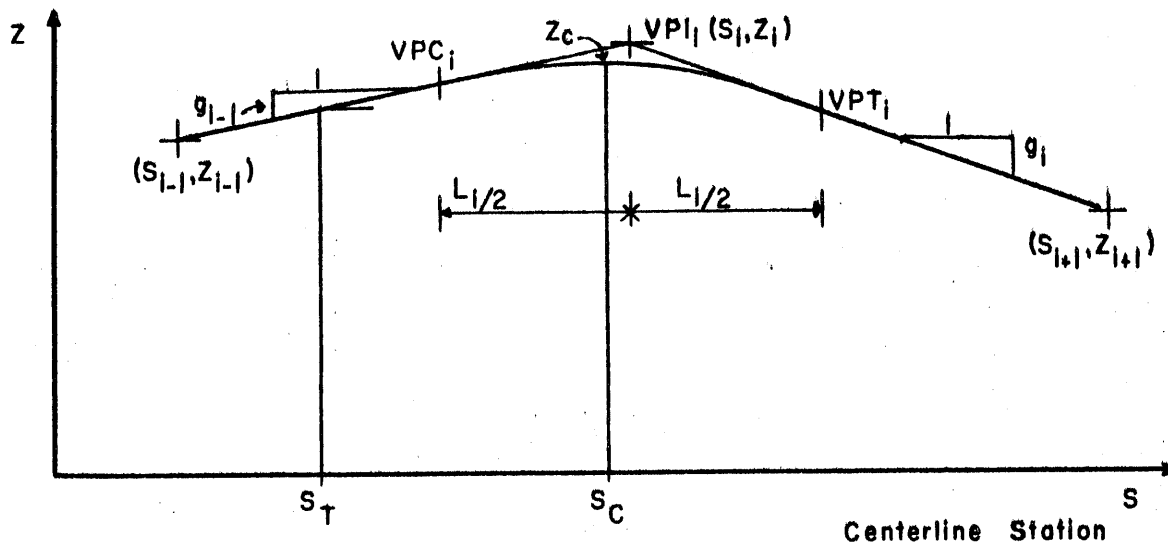
All arithmetic operations are performed in the fixed point mode. All distances and elevations are used with the decimal point three places from the right. Grades are computed with the decimal point to left. Since there are no shift instructions in the program so the number of significant digits in the computed quantities depends solely upon the number of significant digits in the input data.

RESTRICTIONS

- 1 - The alignment must be defined by a minimum of two points.
- 2 - The alignment may be defined by the origin, terminus and any number of curves up to 98.
- 3 - The vertical curves must not overlap, i.e., the centerline station of the PT of one curve must not be greater than the centerline station of the PC of the succeeding curve.
- 4 - The minimum length for a vertical curve is 0.001'.
A length of curve of 0.0' is used to identify the origin and the terminus.
- 5 - The cross section specification cards must be read in order of increasing stations.

SUBROUTINES

No subroutines are used.

MATHEMATICAL ANALYSIS

$$g_i = \frac{Z_{i+1} - Z_i}{S_{i+1} - S_i}$$

$$S_{PC_i} = S_i - \frac{L_i}{2}$$

$$Z_{PC_i} = S_i - \frac{L_i}{2} g_{i-1}$$

$$S_{PT_i} = S_i + \frac{L_i}{2}$$

$$Z_{PT_i} = S_i + \frac{L_i}{2} g_i$$

$$Z_T = Z_i - g_{i-1} (S_i - S_T)$$

$$Z_C = Z_{PC_i} + g_i (S_C - S_{PC_i}) - \frac{(S_C - S_{PC_i})^2 (g_i - g_{i-1})}{2L_i}$$

For a complete treatment of the vertical alignment geometry of a highway see "Route Location and Surveying" by T. F. Hickerson, McGraw-Hill 1953, or any route surveying text.

DTM SPECIAL PROFILE GEOMETRY PROGRAM VA-2GENERAL DESCRIPTION

1. The output of VA-1 is the profile grade elevation at each terrain cross section. Usually these will be at odd stations. Although these elevations are needed for subsequent earthwork computations, they are of little value to the engineer since they usually will be at odd stations.

2. The purpose of VA-2 is to provide profile grade elevations on even stations. The program is loaded with and run immediately following VA-1. It can be used as a separate program for engineering applications.

3. The only additional data which the engineer must furnish is the value of the first even station and the even increment between stations.

DEFINITION OF TERMS

Same as VA-1 plus:

- | | |
|----------|----------------------------|
| S_0 | First even station |
| Δ | Increment between stations |

GENERAL LOGIC OF VA-2

The general logic of VA-2 is the same as for VA-1 with the following exception:

VA-1 computes the profile elevations for values of S taken from the cross section specification cards whereas VA-2 does not use cross section specification cards but generates values of S . This means that where VA-1 reads in a section card VA-2 merely adds the increment Δ to S and returns to compute the Z for this value of S_0 .

INPUT TO VA-2

Same profile-subgrade difference and alignment definition data as VA-1 plus the VA-2 data card:

Word 1	IIIIIIIIII+	Identification
Word 2	SSSSSSS.SSS+	S _o
Word 3	DDDDDDD.DDD+	Δ

OUTPUT OF VA-2

Same vertical curve data as VA-1 plus the even station station data:

Word 1	IIIIIIIIII+	Identification
Word 2	0000000000-	Not used
Word 3	SSSSSSS.SSS+	Even station
Word 4	0000000000-	Not used
Word 5	ZZZZZZZ.ZZZ±	Profile elevation for each even station
Word 6,7,8,9	0000000000-	Not used
Word 10	0080000080	Selects punch format B

EXPLANATION OF BLOCK DIAGRAM

The block diagram for VA-2 is the same as for VA-1 with the addition of Blocks II-1, II-2, II-3 and II-4.

- Block II-1 The value S , the even station whose elevation is determined and which will be increased by Δ , is set at S_0 , the value of the first even station.
- II-2 Switch 2 is set to B since no cross section specification cards are to be read.
- II-3 Switch 4 is set to B and will remain in this position for the remainder of the program.
- II-4 S , whose profile grade has just been determined, is increased by Δ and control returns to Switch 3.

SCALING AND SIGNIFICANT DIGITS

Same as VA-1

RESTRICTIONS

Same as restriction 1,2,3,and 4 of VA-1

SUBROUTINES

No subroutines are used

MATHEMATICAL ANALYSIS

Same as VA-1

APPENDIX D

Program Analysis of DTM Preliminary
Earthwork Program, EW-2. This program is an
example of the type needed for preliminary loca-
tion studies.

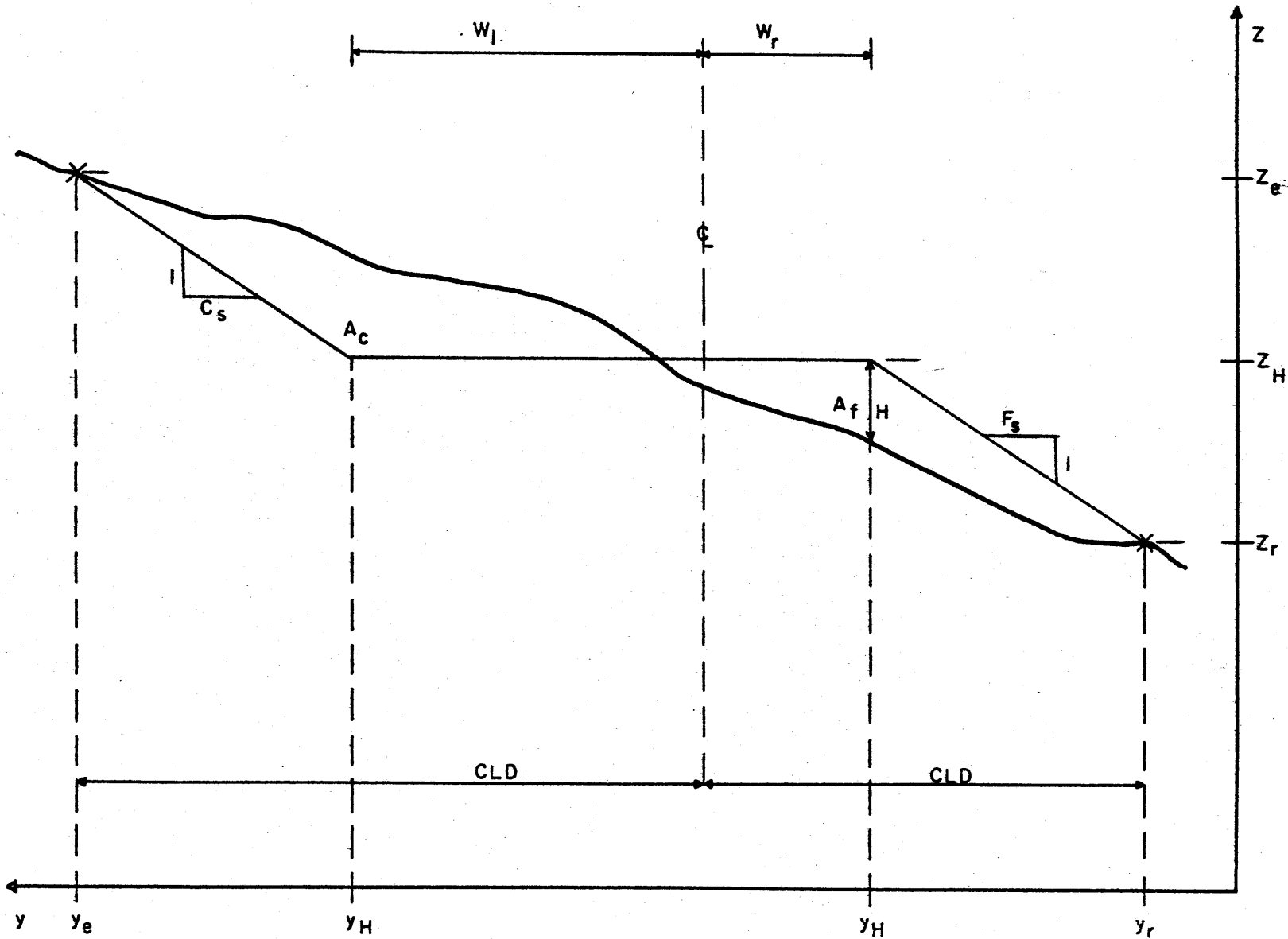
DTM PRELIMINARY EARTHWORK PROGRAM EW-2GENERAL DESCRIPTIONProgram Description and Purpose

1. The EW-2 program computes the location of slope stakes and standard earthwork volume data based on a simply defined template. The input to the computer is the output of the VA-1 program, the terrain data deck, and one or more template specification cards.
2. The EW-2 preliminary earthwork program is intended for rather detailed studies of alternate alignments and grades and for purposes of providing preliminary estimates of earthwork quantities and right-of-way requirements. Since it is not intended for final quantities nor for design purposes, a very simple highway cross section template is used to gain efficiency in computer operation.
3. Earthwork volumes are computed between the DTM terrain cross sections and not between the conventional right angle type cross sections. Similarly, the slope stakes are located along the DTM sections. Except in cases of extreme skew, little difficulty is encountered in visualizing the results.

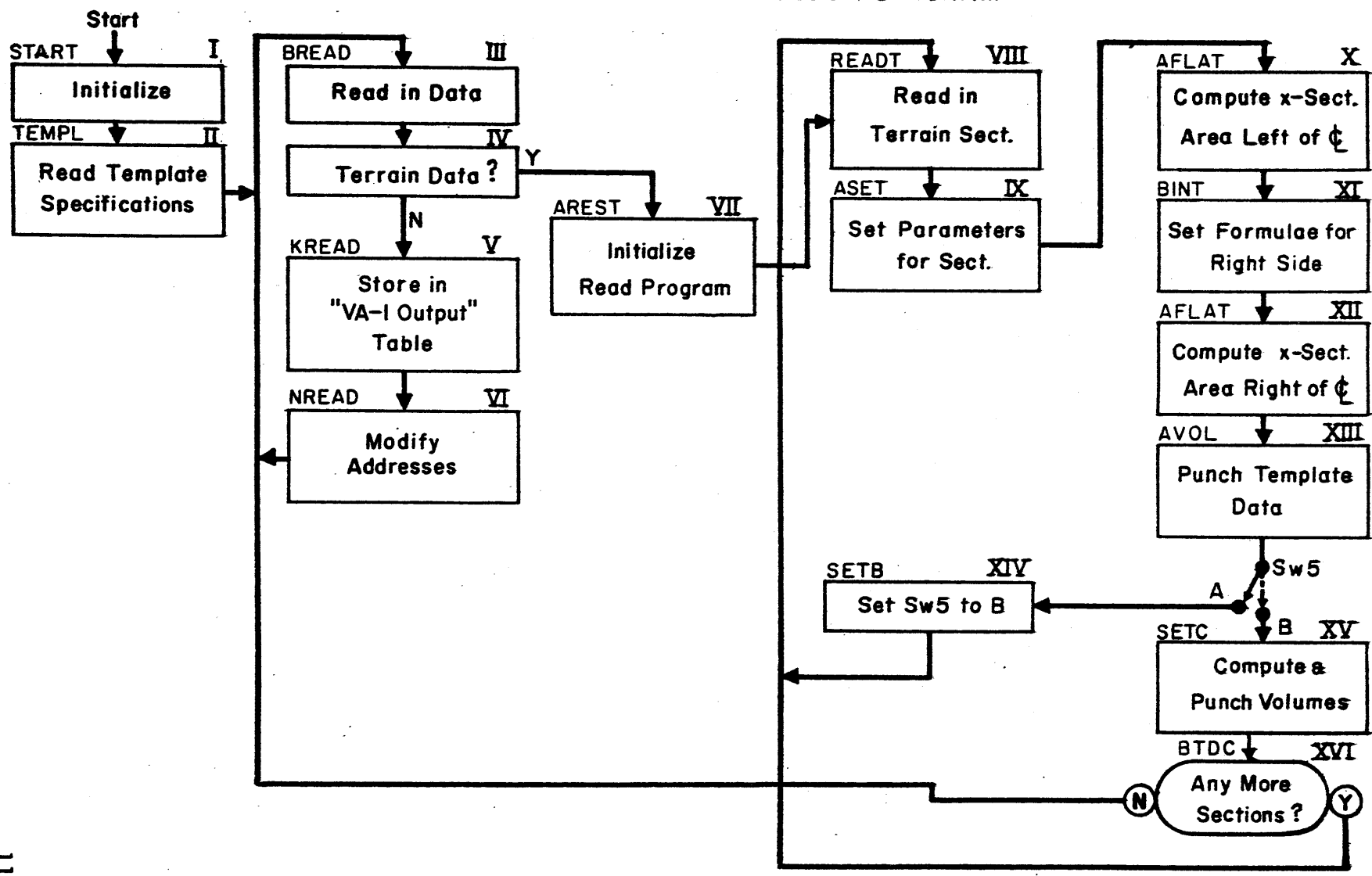
DEFINITION OF TERMS

(See Fig. 8-23:1)

W_l	Distance from ζ to left hinge point
W_r	Distance from ζ to right hinge point
f_s	Slope for a fill less than "H"
F_s	Slope for a fill greater than "H"
C_s	Cut slope
M_f	Multiplication factor for adjustment of fill volumes
M_c	Multiplication factor for adjustment of cut volumes
H	Fill slope criterion
Z_e	Terrain elevation at centerline
Y_ζ	Baseline y-coordinate of the centerline
Z	Template elevation at a section
ψ	Skew angle, angle between normal section and scan line
CLD	Distance from ζ to slope stake measured along a scan line
Z_H	Terrain elevation of hinge point
Y_H	Baseline y-coordinate of hinge point
Y_l	Baseline y-coordinate of left slope stake
Y_r	Baseline y-coordinate of right slope stake
A_c	Cut volume for one section
A_f	Fill volume for one section
C	A code used in the output for each side of the template indicating the side slope used.
	$C = 1$ for C_s
	$C = 2$ for f_s
	$C = 3$ for F_s
x_j	Baseline x-coordinate of a cross section j
Y_i	Baseline y-coordinate of terrain point i
z_i	Elevation of terrain point i
$\cos\psi_j$	Cosine of skew angle of cross section j



EW-2 MACRO BLOCK DIAGRAM



MIT - MDPW - BPR

DTM MANUAL

8-23:4
12/1/58

Fig. 8-23:2

11/59

GENERAL LOGIC OF EW-2

(See Fig. 8-23:2)

1. Basically, there are two types of input to the program, the cross section specification data and the terrain data sections. Since only one input is available on a basic machine the input must be staggered. Therefore a block of cross section specification data is read in and stored then the terrain data sections are read in one at a time. The amount of cross section specifications data read in and stored depends on the storage available. When the stored data has been used up a new block of data is read in.

2. The major part of the program is concerned with computing the cut and fill areas for a section. The computations are broken up into four parts; from the centerline to the left hinge point, from the left hinge point to the left slope stake, from the centerline to the right hinge point, and from the right hinge point to right slope stake.

The equations used for computing the areas from the centerline to the left hinge point are the same for cut as for fill and are very similar to the form needed for computing the areas from the centerline to the right hinge point. For this reason the same instructions are used for the right as for the left with the necessary changes being made after the left computations are concluded.

The equations used in calculating the fill area from the left hinge point to the left slope stake are similar to those for the cut area. For this reason the same block of instructions is used for cut that is used for fill with the changes being made when the slope is chosen.

The equations for the right side are similar to those for the left and the same instructions are therefore used, again with the necessary changes being made after completion of the left side.

3. The first cross section will have template data associated with it, but no volume data. Therefore Switch 5 is used to by-pass Block XV.

INPUT TO EW-2

The input is shown as it appears to the computer as opposed to the way it is punched on the cards.

Template Specification Data

The data specifying a particular template is read in on a load card. The template may be changed at any point by inserting a new template card immediately following the beginning-of-line card of the first cross section to use the new template. This new template will be used at all sections which follow until another template specification card is met.

Word 1	RRRRRRR.RRR+	Distance from centerline to right hinge point (W_r)
2	LLLLLLL.LLL+	Distance from centerline to left hinge point (W_l)
3	fffffff.fff+	Low fill slope (f_s)
4	FFFFFFF.FFF+	High fill slope (F_s)
5	CCCCCCC.CCC-	Cut slope (C_s)
6	xxxxx.xxxxx+	Fill multiplication factor
7	xxxxx.xxxxx+	Cut multiplication factor
8	HHHHHHH.HHH+	Fill slope criterion (H)
9,10	000000000+	Not used

Cross Section Definition Data (VA-1 Output)

Word 1	0009000000+	Identifies this format
2	xxxxxxxx.x00+	Baseline x-coordinate of this section
3	0SSSSSS.SSS+	Centerline station of this section
4	000yyyy.yyy+	Baseline y-coordinate of the centerline
5	000ZZZZ.ZZZ+	Ground elevation at centerline
6	000ZZZZ.ZZZ+	Centerline grade elevation
7	C.CCCCCCCCC±	Cosine of skew angle, ψ
8	0000000000+	Not used
9	0000000000+	Not used
10	IIIIIIIIII+	Identification

Terrain Data

For input formats see 4-06:7

OUTPUT OF EW-2

The output is shown as it appears to the computer as opposed to the way it is punched on the cards.

Template Definition Data

Word 1	IIIIIIIIII+	Identification
2	xxxxxxx.xxx+	Baseline x-coordinate of section
3	YYYYYYY.yyy+	Baseline y-coordinate of left slope stake
4	00C00ddd.dd+	"C" is code indicating the left slope used. "d" is the left CLD
5	zzzzzzz.zzz+	Left slope stake elevation
6	YYYYYYY.yyy+	Baseline y-coordinate of right slope stake
7	00C00ddd.dd+	"C" is code indicating right slope used. "d" is right CLD
8	zzzzzzz.zzz+	Right slope stake elevation
9	000000000-	Not used
10	0080008000+	Select punch format A.

Note: If no slope stake is located because of insufficient terrain data word 3 and/or word 6 will have the value of 999999999+

Volume Data

Word 1	IIIIIIIIII+	Identification
2	xxxxxxx.xxx+	Baseline x-coordinate of section
3	VVVVVVVVVV.+	Cut volume between this and preceding section
4	VVVVVVVVVV.-	Fill volume between this and preceding section
5	VVVVVVVVVV.-	Adjusted fill volume between this and preceding section
6	VVVVVVVVVV.+	Accumulated adjusted cut volume
7	VVVVVVVVVV.-	Accumulated adjusted fill volume
8	MMMMMMMMMM.±	Mass haul ordinate
9	000000000-	Not used
10	0080000000+	Selects proper format

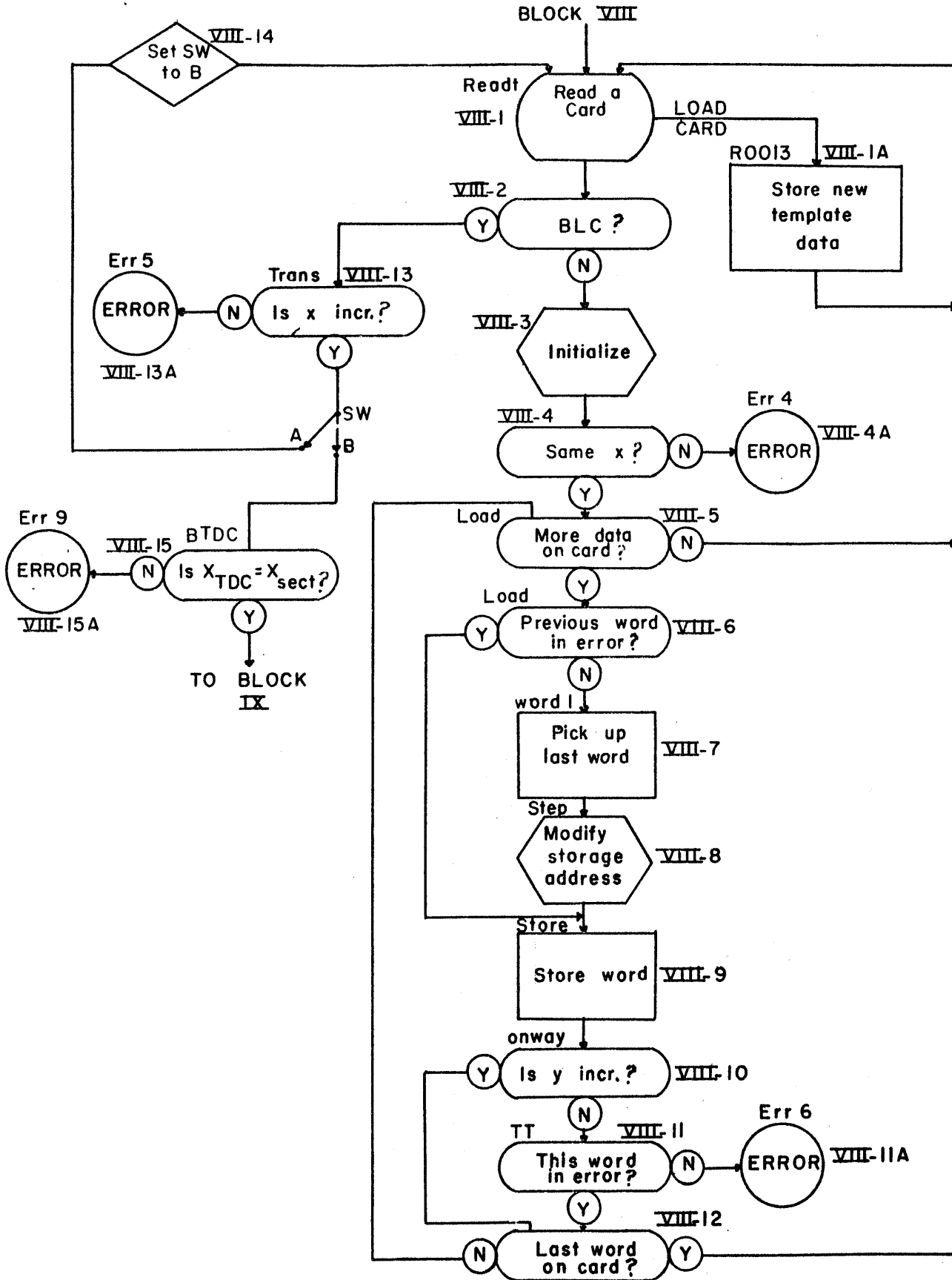


Fig. 8-23:3

BLOCK IX

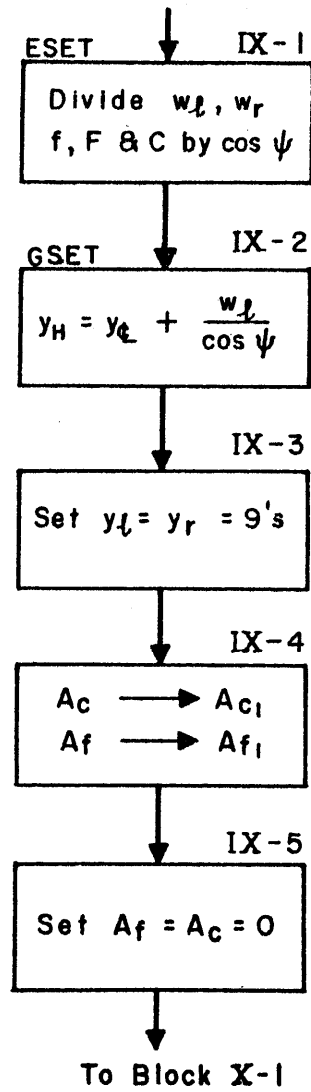


Fig. 8-23:4

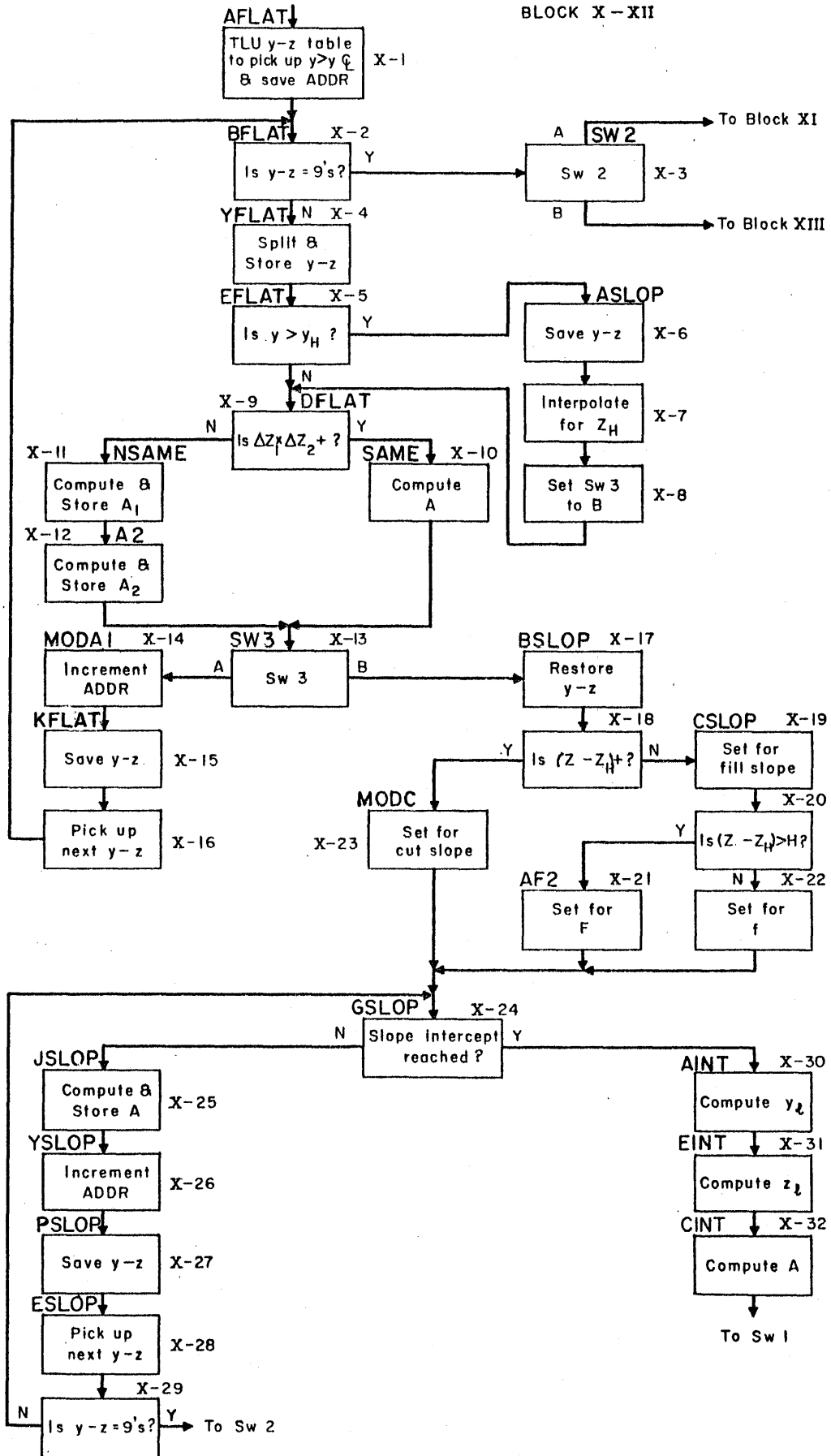


Fig. 8-23:5

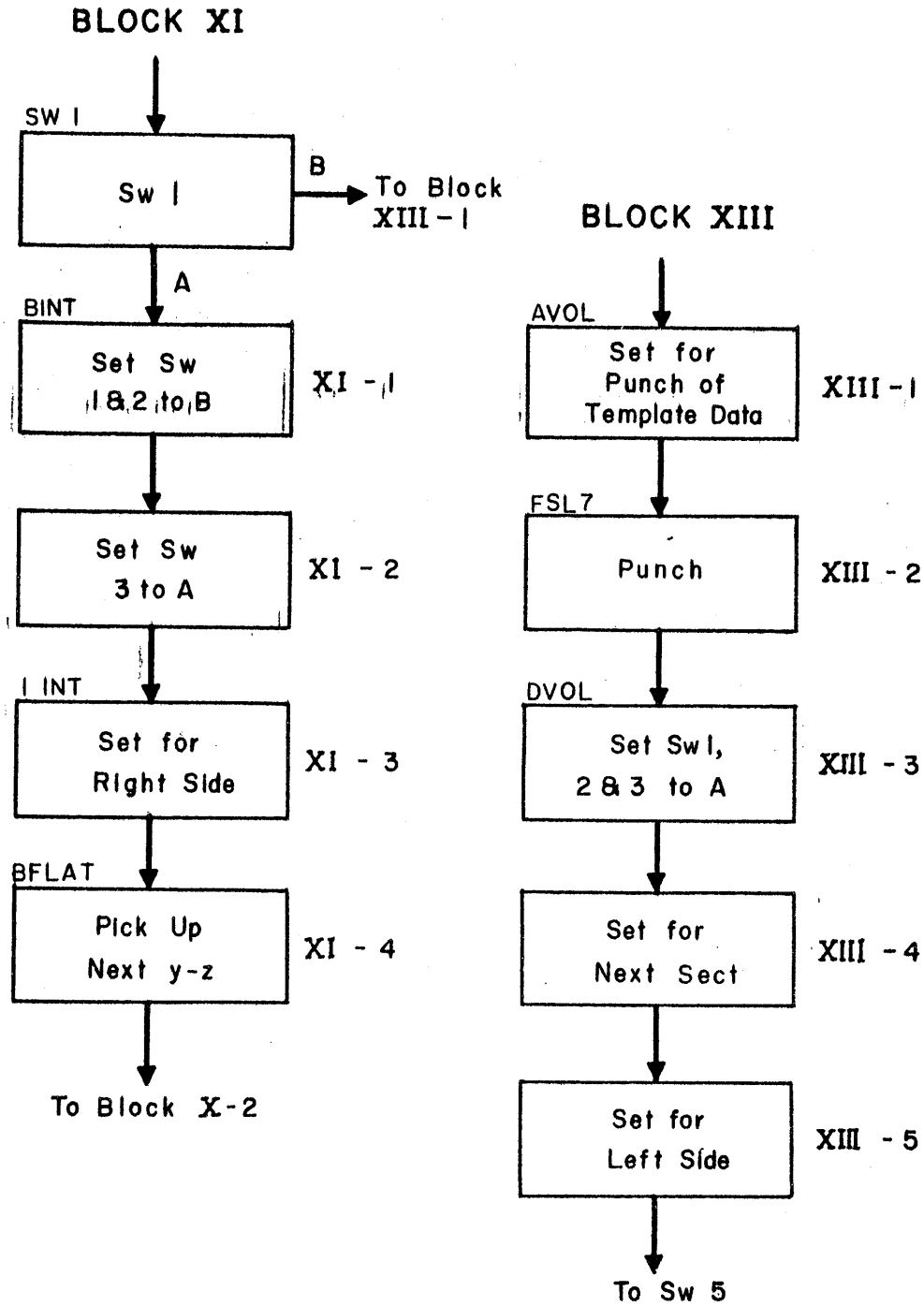


Fig. 8-23:6

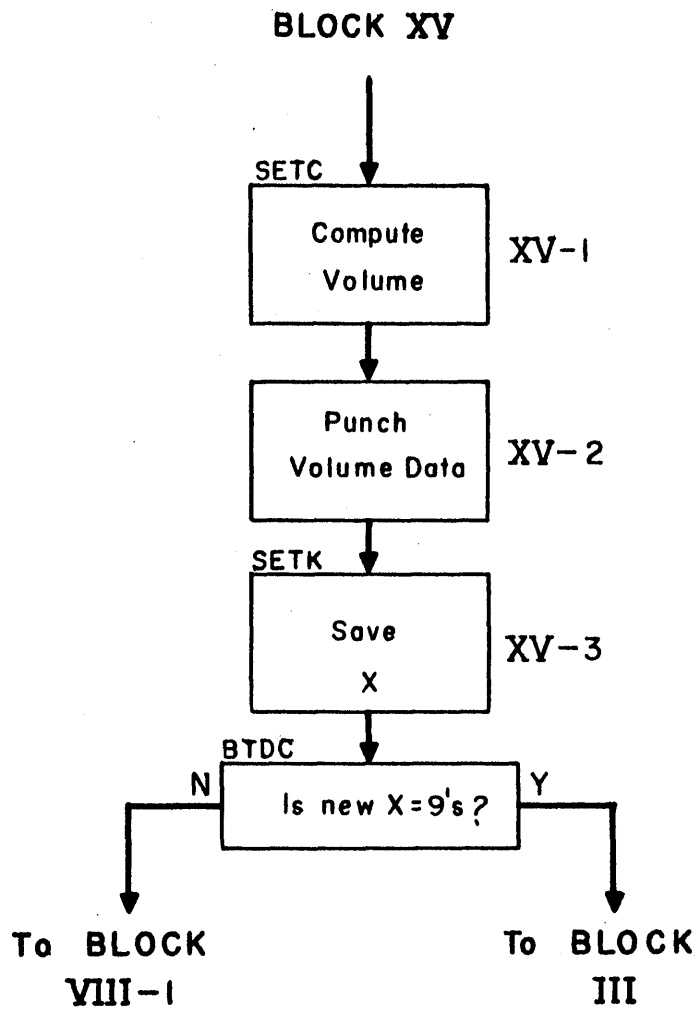


Fig. 8-23:7

SCALING AND SIGNIFICANT DIGITS

All arithmetic operations are in the fixed point mode.

Distances and Elevations -	three decimal places
Areas -	Sq. ft. to three decimal places
Volumes -	Nearest cubic yard
Cosine ψ	Nine decimal places
M_f, M_c	Five decimal places

SUBROUTINES

No subroutines are used

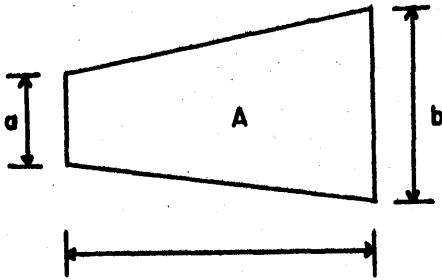
RESTRICTIONS

1. Terrain Data - same restrictions as HA-1
2. The maximum number of cross section definition cards that may be read in a block is 99.

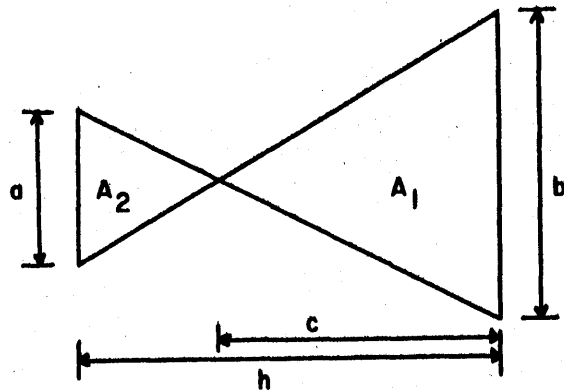
MATHEMATICAL ANALYSIS

Correction for Skew Angle: Since the template is defined normal to the centerline the given values are divided by the cosine of ψ to correct for the skew.

Interpolation of Elevations: Linear interpolation is used for determining the terrain elevations at the hinge points.

Cross Sectional Areas:

$$A = \frac{1}{2} h(a+b)$$



$$A_1 = \frac{1}{2} \frac{|b|(b)}{|a|+|b|} (h)$$

$$A_2 = \frac{1}{2} \frac{|a|(a)}{|a|+|b|} (h)$$

$$c = \frac{|b|}{|a|+|b|} (h)$$

Volumes: The average end area method is used.

$$V = \frac{1}{2} (A_1 + A_2)$$