Final Engineering Report on Terrain Geometry Measurement

by I. Sattinger

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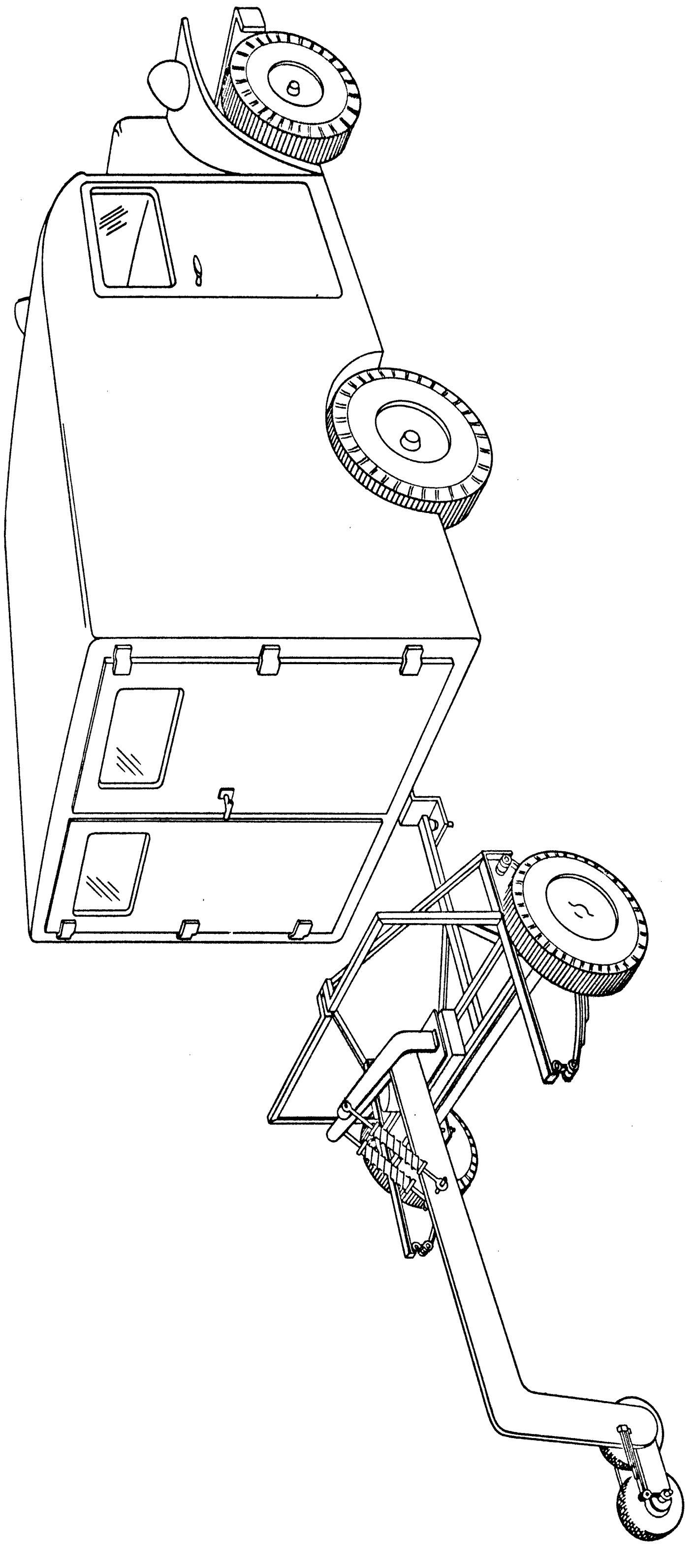

FIELD EQUIPMENT FOR TERRAIN MEASURING SYSTEM

I

INTRODUCTION

The Engineering Research Institute of The University of Michigan, under Contract DA-20-018-ORD-13754 with the Land Locomotion Research Laboratory of the Detroit Arsenal, has conducted a research program to determine the most suitable method of measuring terrain geometry and to prepare a preliminary design of the type of measuring system selected. This system would provide a means for the large-scale collection of terrain data to be used as the basis for improved methods of analysis and development of cross-country vehicles. The contract was initiated on 14 April 1955 and terminated on 30 April 1956. This report summarizes the work performed under this contract.

1.1 CONCLUSIONS

The research program described in this report has resulted in the following conclusions:

1. The most suitable method of measuring terrain geometry with the required speed, accuracy, reliability, and convenience is the slope integration method, in which a trailer is towed along the ground to obtain a record of ground slope data as a function of distance traveled.

2. The most satisfactory method of measuring terrain geometry uses a set of field equipment to produce a punched paper tape record of ground slope for constant increments of advance along the ground. This record is converted by means of a digital computer to another paper tape record of increments of change of elevation for constant increments of horizontal distance. Finally, the output of this record is converted to analog voltage form, compensated by special frequency-selective circuits, and is integrated to provide a d-c voltage representing elevation for a constant value of horizontal speed.

3. The performance capabilities and the optimum design of this system can be determined only by constructing and testing an experimental model of the system. Since a number of the design features and parameters of the system depend on subsequent methods of using the data and on the total amount of data required, further detailed studies of the methods of application of the data should accompany the experimental program so that firm system design decisions can be made.

4. A research program has been outlined covering (a) the design, construction, and test of an experimental model of the proposed system; (b) the conduct of additional design studies and operational analyses; and (c) the preliminary design of a prototype system. It is estimated that this program will cost $34,000 and will require 23 man-months of technical effort and 12 months for completion.

1.2 BACKGROUND

The Land Locomotion Research Laboratory approached the Engineering Research Institute of The University of Michigan in the summer of 1954 with the request that the Institute explore the possible methods of recording the roughness of ground surface. This move was an outcome of the growing realization that the geometry of the terrain surface is as important to the mobility of motor vehicles as are the physical properties of the ground.

Although a first systematic analytical approach in this direction was made by Lehr prior to 1944 (Ref. 5), the whole question was not sufficiently recognized until the early 1950's when Bekker reformulated the problem in his lectures delivered at the Graduate School, Stevens Institute of Technology ("A Theory of Land Locomotion – The Mechanics of Vehicle Mobility," to be published in the fall of 1956 by The University of Michigan Press), and stressed it again during his studies at the Operations Research Office, The Johns Hopkins University (Ref. 4).

The study of ground wave performance is a matter of increasing importance in the search for ways to increase the allowable speed of cross-country vehicles over rough ground. The development of a suitable methodology for dealing with this aspect of land locomotion requires research in two main directions.

First, accurate comprehensive information on the geometric characteristics of the terrain over which cross-country vehicles must operate is needed to replace the present sketchy and incomplete information. This requires a research program for the collection of such data on representative samples of the earth's surface and the analysis and organization of these data.

Second, techniques must be further developed for predicting vehicle performance over given terrain from known vehicle characteristics. In addition to experimental field testing, a considerable amount of work has been done in the field of theoretical analysis of vehicle performance. The early methods of theoretical analysis were based primarily on the assumption that the suspension system of cross-country vehicles is linear (Ref. 5 and 6). More recently, however, methods based on the use of the analog computer have been developed which take into account the important non-linearities of the suspension system as well as the irregular character of the ground surface (Ref. 7 and 8).

The research program described here represents an initial step in the first area of research described above, namely, the collection and analysis of data on terrain geometry.

1.3 SUMMARY OF WORK PERFORMED

The types of information required on terrain geometry include the profile data of particular sections of ground, and auxiliary data identifying the specific path along which the profiles have been obtained. Most of the emphasis in the research program has been devoted to the problem of profile measurement, since reasonably simple solutions of the route measurement problem are available.

The basic requirements of a profile measuring system were established in terms of accuracy, economy, simplicity of operation, mobility, and usability of the form of output data (Sec. 2). With respect to vertical accuracy required, errors of 1 or 2 inches over a horizontal distance of 10 feet, or 4 inches over a distance of 100 feet are considered acceptable. A maximum allowable speed of 10 fps for the field equipment is desirable. The output of the complete system should be a d-c voltage representing to a suitable scale factor the elevation of the ground along a path being traversed at a constant horizontal velocity.

In order to select the most suitable method of profile measurement, consideration was given to the following:

1. conventional surveying methods,
2. hydrostatic leveling systems,
3. highway roughness measuring devices,
4. aneroid barometer methods,
5. slope integration methods,
6. aerial photogrammetric techniques,
7. sonic altimeters, and
8. radar altimeters.

A comparison of these methods (Sec. 3) resulted in the conclusion that the slope integration method most nearly meets the requirements previously stated.

This method was analyzed in detail (Sec. 4). The analysis laid the groundwork for establishing the organization of the data-processing system and for comparing alternative methods of mechanization, and also determined the limitations in attainable accuracy.

On the basis of results of this analysis, a preliminary design of a complete measuring system was prepared (Sec. 5.1). The field equipment consists of a trailer towed by a wheeled vehicle. The trailer contains a measuring assembly which continuously measures the slope of the ground by means of a tandem arrangement of two 11-inch diameter wheels on a 12-inch wheelbase. The assembly also indicates constant increments of motion along the ground. These data are recorded on punched paper tape in digital form by means of a high-speed tape-punching mechanism. The tape record is then returned to the laboratory, where the information is processed by digital computation techniques and by a special-purpose computing system to produce a d-c analog voltage of the form desired.

The performance capabilities and optimum design of this system can be determined only by experiment (Sec. 5.2). To accomplish this, an experimental version of the system must be constructed and tested. Information obtained from this test program plus certain additional system analyses can then be used to prepare the design of a prototype measuring system. Such an experimental program is estimated to cost $34,000 and to require a total completion period of 12 months (Sec. 5.3).

II

SYSTEM REQUIREMENTS

2.1 TYPES OF INFORMATION REQUIRED

The profile data of a particular section of ground form a record of the elevation of each point along a selected route as a function of the horizontal distance along the route. Methods of analysis of the ground wave performance of cross-country vehicles make use either of a ground profile record or of some other form of data derived from it. Profile data are thus the basic information required in a terrain measuring program.

If the data are to be used to determine the dynamic response of the vehicle in pitch and bounce only, then it will be sufficient that the profile along a single line be obtained. To make more comprehensive studies which include the roll response, data must be collected along two parallel lines separated by the track width of a vehicle.

Since studies of vehicle mobility may be expected to cover entire areas (Ref. 4, pp. 38-41), the profile data collected along specific paths should be supplemented with information covering the general area in which the data were taken. Therefore, a plan view of the area should be provided to show the natural and man-made features. Such topographical data may already be available either in the form of topographic maps like those prepared by the U. S. Geological Survey or in the form of aerial photographs available from civilian or military agencies. In addition, information should be obtained about the geological character of the area and the physical characteristics of the soil.

To indicate the particular route along which a set of profile measurements is taken, a record should be made of the plan view of the route. This plan view might be made with sufficient accuracy by simply marking the route on a map. An automatic method capable of good accuracy is also available in the form of the odograph, discussed in Section 3.1.

Since selection and preliminary design of a suitable method of obtaining terrain profile data are the primary aims of the present contract, determination of suitable sources or methods of collection of supplementary data on the topology and geology of the areas studied has not been given major attention.

2.2 PERFORMANCE AND OPERATING CHARACTERISTICS OF PROFILE MEASURING SYSTEM

The basic requirements of a profile measuring system include accuracy, economy, reliability, mobility, and usability of the form of output data.

The accuracy required of the data depends on the effect which errors in profile measurement have on the calculation of the pitch, bounce, and roll of a number of types of wheeled and tracklaying vehicles as they travel over terrain at various speeds. In terms of response to a sinusoidal road function of a given amplitude, only small motions of the vehicle chassis occur for ground wave lengths less than about one-half or greater than five times the wheelbase or ground contact length of the vehicle being studied. Wheelbases of interest range from 4 to 20 feet; therefore, reasonably accurate measurements of sinusoidal components with wave lengths greater than two feet and less than 100 feet should be sufficient. To obtain acceptable accuracy for the short wave length components, a horizontal resolution (i.e., horizontal spacing of individual measurements) equal to about one foot is adequate. However, a greater degree of horizontal resolution is useful, since it permits detailed measurement of individual non-sinusoidal irregularities. With respect to vertical accuracy required, errors of one or two inches over horizontal distances of the order of a wheelbase length result in chassis motions small enough to be ignored. Such vertical errors may accumulate to several times this amount over distances of 100 feet. An allowable error of four inches accumulated over a distance of 100 feet would seem to be a reasonable specification for vertical accuracy. In determining the accuracy of a system, the closure error over distances which are large compared to the wheelbase lengths of interest should be prorated (Ref. 9, p. 5), since systematic errors accumulating in one direction only appear as a difference in average slope and are therefore of no significance in vehicle studies.

The economy of a particular measurement method should be considered both in terms of its total cost, which includes the initial cost of the measuring system (including the cost of development), and in terms of the cost of operation and maintenance of both field and laboratory equipment. A measure of the total cost is the cost per unit-distance covered. The fraction of the initial cost of the system chargeable per unit distance covered will be inversely proportional to the total distance to be measured. Although no accurate estimate of this total can be made in advance, it would probably exceed 1000 miles. The cost of field operations per unit-distance covered is largely determined by the speed of ground coverage, because of the high cost of maintaining men and equipment in the field.

Reliability of operation and ease of maintenance are important characteristics of a suitable system, both in terms of cost and of administration, since a data collection system which depends upon highly trained technical personnel is expensive and might be difficult to administer if personnel is not readily available.

Mobility is a further necessary characteristic of the system. The ground over which measurements are to be made will contain obstacles of various sizes and shapes, will vary widely in composition or consistency, and may be covered with snow or vegetation. In many cases difficulty will be experienced in reaching the location where measurements are to be made.

Two ultimate uses for terrain geometry data are anticipated: to provide road-function inputs to an analog simulation of a vehicle suspension system, or to be subjected to harmonic analysis techniques in order to characterize each road sample in terms of its spectral density, i.e., the amplitude of each sinusoidal component as a function of ground wave length. In either case, the data supply a record capable of providing a d-c voltage proportional to elevation, y, as a function of the horizontal component of distance, x.

For purposes of harmonic analysis, a wave analyzer is used. For this application the analog voltage representing y is required for the condition of x increasing at a constant rate, i.e., dx/dt constant. On the other hand, if the profile data are to be used in an analog simulation, it may be necessary to produce a voltage representing y under the condition that dx/dt is controlled to vary over a wide range. The preparation and use of a record capable of producing y voltage for continuously varying dx/dt is more properly a part of the analog computer operation than of the terrain measuring system. Therefore, it is considered satisfactory for the output of the measuring system to be a d-c analog voltage representing elevation, y, for constant values of dx/dt.

For studies of roll response, profile data must be obtained along two parallel tracks. This may require duplication of certain equipment or measurements. Since this duplication presents no inherent difficulty, the discussion of the terrain measurement problem is confined to methods for obtaining a single track.

III

STUDY OF METHODS OF TERRAIN MEASUREMENT

3.1 USE OF ODOGRAPH FOR ROUTE RECORDING

For a vehicular type of field system, the odograph provides a satisfactory method of automatically recording a plan view of the path followed by the terrain measuring system. In one form of the device (Ref. 10) the unit contains a magnetic compass which reads the magnetic heading of the vehicle and an auxiliary speedometer cable for measuring the distance traveled. A computing device combines the readings taken by the compass and the speedometer, converting them into distances traveled north-south and east-west. The output of the computer causes an automatic plotting table to record a plan view of the path traveled.

One new system of this type is known to be under development at the Sun Physical Research and Development Laboratory at Newton Square, Pennsylvania. This is the same organization which has been associated with the Johnson Elevation Meter mentioned in Section 3.2.2.3. Tests run on an experimental model of the odograph indicate that an accuracy of 1 part in 500 is obtainable. Since this system is still under development, cost information is not available.

Another system is under development by Engineer Research and Development Laboratories, Corps of Engineers, Fort Belvoir, Virginia, under Project 8-34-14-106. This system is intended for use as a combat vehicle navigator with an intended accuracy of 1 part in 100. It is estimated that this system would cost $7,000 to $8,000 as a position indicator, and that costs might run up to $10,000 if a plotting device were added.

3.2 METHODS OF PROFILE MEASUREMENT

In the study of available methods of profile measurement, all those which appeared to have even a remote possibility of application to the specific problem involved were carefully considered. The various systems can be divided into those which must be hand-carried, those which can be mounted on a ground vehicle, and those which can be airborne.

The hand-carried systems discussed here include conventional surveying methods and hydrostatic leveling systems. Among the vehicular systems are included highway roughness measuring devices, a vehicular system incorporating a barometric device, and slope integration systems. Among the airborne systems, aerial photogrammetry and sonic and radar altimeters are discussed. For reasons given in Section 3.2.4, the slope integration method has been selected as the most suitable.

3.2.1 Hand-Carried Systems

3.2.1.1 Surveying Methods

The conventional method of ground profile measurement makes use of the engineer's level and target rod. Professor Edward Young of The University of Michigan's Civil Engineering Department has estimated that for terrain which is not too difficult to traverse, a surveying crew of four men can run about one mile of profile per day at an estimated personnel cost of $56. Young has further estimated that two man-days are required to convert the raw data into a profile plot. The total cost of one mile of profile is therefore estimated to be about $100. This figure would be increased for inaccessible or difficult terrain. Additional processing of the data would be required to convert it to the required form of an analog voltage. Surveying is capable of producing data with more than sufficient accuracy, but is an expensive method if large quantities of data are needed, especially if fine horizontal resolution is required.

3.2.1.2 Hydrostatic Leveling Systems

To increase the speed with which elevation measurements are made, Crumrine and Palmer (Ref. 11) have developed a hand-carried leveling system which indicates differences in elevation by measuring the pressure head of a column of water. This system is essentially a differential pressure gauge connected by a length of water-filled plastic tubing to a small water reservoir. On unsupported traverses (i.e., measurements without intermediate or final bench marks), the instrument is capable of indicating elevation differences over distances of three to five miles to a probable error of about four inches and a maximum error of 20 inches. The range of the instrument is from minus to plus 10 meters (32.8 feet) marked off in intervals of 2 cm (0.8 inch) which can be read to the nearest centimeter. The device more than meets the accuracy requirements (Sec. 2.2).

In terms of the speed of operation, it has been estimated (Ref. 11) that the speed of traverse with the hydrostatic level in rugged, brush-covered areas is from two to five times faster than with an optical level. The average speed of traverse was about one mile per hour over a rugged, brush-covered test course and from 1.5 to 2 miles per hour on roads. Of course, for detailed measurement of profile with readings taken at all break points in the ground, the speeds which could be obtained would be considerably less than the values given above.

Since ground profiles may be needed of terrain for which the hydrostatic level was developed, the potentialities of hydrostatic leveling systems were considered in detail. A brief analysis was made and a considerably different mechanization of the hydrostatic principle was conceived to provide for automatic data recording (Ref. 1).

The device would consist of two target rods, each carrying a vertical transparent tube, the two tubes being connected together by a 15-foot length of plastic tubing. By setting the rods vertically at two points on the ground and manually lining up an index assembly on one of the rods with the water level, the horizontal and vertical components of distance between the two points could be recorded in digital form on photographic film. A laboratory data reduction system would be provided to convert the recorded data into usable form for subsequent analysis. With this type of measurement system, it would be possible for two operators to take measurements at the rate of four per minute, each measurement consisting of the entire operation of moving forward to a new position, leveling the rods, adjusting the index assembly, and inserting the data into the recorder. The actual speed would depend on the roughness of the terrain and the corresponding average interval between points of measurement. For favorable terrain, the average measurement interval might be as great as five feet, in which case a forward velocity of 1200 feet per hour would be attained. Making necessary allowances of time for travel to and from the area to be measured and for interruptions, this method would probably result in a speed somewhat greater than one mile per day. This is slightly faster than the speed obtainable when the optical level is used. This method would require fewer field personnel,and would provide the measured data in form suitable for automatic data processing. The error of the individual measurements of elevation difference is less than one inch. The attainable horizontal resolution of the system is also very good, since the two rods can be placed practically side by side to obtain fine detail on sharp irregularities such as large stones. However, it would not be economical to obtain such fine resolution for more than a small percentage of individual measurements.

3.2.2 Vehicular Systems

3.2.2.1 Highway Roughness Measuring Devices

Since terrain measurement involves problems similar to those encountered in the measurement of highway roughness, two specific instruments which have been used for this purpose were investigated.

One instrument, known as a roughometer (Ref. 12), consists of a standard automobile wheel attached to a 600-pound frame by means of an automobile spring and a shock absorber. The instrument responds essentially as a single wheel of an automobile. The device is towed along the highway at a speed of 20 miles per hour and indicates surface roughness by a mechanical arrangement which totalizes all upward motion of the wheel with respect to the frame. The measurement of the total motion in terms of inches of vertical motion per mile of horizontal travel thus becomes an indication of the roughness of the highway surface.

The other surface-measuring device, known as a profilograph (Ref. 13), gives a more direct measurement of surface roughness. The body of a vehicle is mounted on a complex mechanical assembly of 16 wheels, arranged in such a way that the center point of the body is always at a height corresponding to the average height of the road at the 16 points of wheel contact. A seventeenth wheel contacts the road at a point below the center of the vehicle body; and a measurement of the height of this wheel with respect to the center of the body thus becomes a measure of the height of the road surface at that point with respect to the average height of the road surface at the other 16 contact points.

Although the functions of both the roughometer and the profilograph are similar to those required for terrain measurement, the principles of operation involved are not adaptable to the present problem. The roughometer does not give information in terms of terrain elevation. The profilograph does not measure terrain elevation with respect to a fixed point. In addition, the magnitude of the irregularities which are encountered in terrain measurement makes it impractical to use either these devices or modifications of them.

3.2.2.2 Measurement by Aneroid Barometer

Experimental aneroid barometers have been constructed capable of providing an instrument precision equivalent to 0.3 foot of elevation difference (Ref. 14). In the design of these units, particular stress was placed on sensitivity and precision at the expense of portability and convenience of operation. Although the attainable accuracy approaches that required for terrain measurement, it cannot be considered adequate. Furthermore, severe difficulties would be encountered in attempting to adapt the principle to a practical device for terrain measurement. A system which would operate with a minimum of manual control would be complex, and the ultimate accuracy of the system would be limited by the effect of transportation shocks, temperature variations, and time delays in the stabilization of the air pressure within the measuring chamber. The barometric method is therefore not considered applicable to the present problem.

3.2.2.3 Slope Integration Methods

Among the slope integration methods, the most recent development is the Johnson Elevation Meter (Ref. 9, 15, and 16). Since this instrument is intended chiefly for use in measuring total elevational differences between points which may be as widely separated as several miles, the data provided by it would not be usable in terrain measurement. However, the integration of ground slope, which is the basic principle of operation, is adaptable to a profiling instrument.

To perform its function, a device based on the slope integration method is designed so that it mechanizes the equations:

$$y - y_o = \int_o^s \sin\theta \, ds, \tag{3-1}$$

$$x = \int_o^s \cos\theta \, ds, \tag{3-2}$$

in which s is the total distance traveled along the surface of the ground,

y is the elevation of the ground for total travel, s;

y_o is the elevation of the ground at the beginning of the run;

x is the horizontal component of distance along the ground for total travel, s; and

θ is the slope angle of the ground under the vehicle at the distance s from the origin.

For these equations, the two quantities which must be measured continuously are the distance traveled by the vehicle and the slope of the ground over which the vehicle is traveling. To determine these two quantities, a trailer towed by a powered vehicle supports a measuring assembly consisting of two wheels mounted in tandem so as to follow a common track. An angular reference device carried by the trailer provides a continuous indication of the pitch angle of the measuring frame, assumed to be the same as the slope of the ground over which the wheels are traveling. The forward travel of the vehicle is measured by an odometric device connected to one of the trailer wheels. The electrical outputs of the angular reference and the distance indicator are fed directly or through a recording medium to a computer which uses these outputs to perform the mathematical computation indicated in Equations 3-1 and 3-2.

The results of the study of available methods have indicated that the slope integration method would most nearly meet the requirements for a means of collecting terrain data on a large scale. For that reason, the method is discussed in detail in Sections 4 and 5.

3.2.3 Airborne Methods

3.2.3.1 Aerial Photogrammetric Techniques

Aerial photogrammetry is a well-established method of obtaining information on earth shapes in plan view, and, by the use of stereoscopic techniques, in elevation (Ref. 17). The current method in use for obtaining the topography of an area is to fly a relatively straight course over the area, making successive photographs at short enough intervals so that adjacent pairs have considerable overlap and may be used as stereo pairs. Several types of optical equipment are in use for extracting elevation information from the stereo effect; these are intended primarily for tracing lines of constant elevation on a map made from the photographs.

Another system of aerial photography uses a strip film camera which makes a continuous film record rather than successive exposures. Such a camera, known as the Sonné camera, has been developed by Chicago Aerial Industries. In the Sonné camera, the continuously moving film passes behind two separate lenses. The rate of film advance is made proportional to the ground speed and inversely proportional to altitude so as to form a sharp image. Two slits, which serve as shutters because of the film motion, are displaced laterally to expose the film in two adjacent strips. Hence, a stereo effect is available for use in determining elevations. To obtain profile data from the film, an optical viewing device equipped with adjustable "floating dot" reticles and a continuous film drive mechanism could be used. The motion of the reticles made by an operator in keeping the dot in apparent contact with the ground and the motion of the film advance mechanism could then both be coupled to a plotting table to produce continuous profile plots.

Where the newest types of optical equipment for analysis of the aerial photographs are employed, the normal limit of accuracy of elevation data is about two feet; but by making photographs at lower altitudes than normal, so that a photographic scale of one inch to 500 feet could be used, and by taking extra precautions in data reduction, an accuracy of perhaps six inches could be attained. To obtain greater accuracy than this, a helicopter would be required to permit flight at lower altitudes and slower speeds. The use of a helicopter would also permit selection of routes more nearly approximating those which would be followed by a vehicle on the ground.

Because present photographic techniques are aimed generally toward drawing contour maps of the surveyed area, they are not directly applicable for present purposes. It would be possible, however, to make a minor modification of one of the plotting machines to make continuous profile plots. The estimated total cost to produce profile plots is between $100 and $300 per mile, the variation in unit cost depending to some extent, upon the distance of the surveyed areas from commercial airfields. A substantial portion of the cost of this operation is in the operation of processing the data from the completed photographs.

In the present application, aerial photogrammetric techniques offer several advantages. They provide relatively large area coverage as opposed to what may be termed the linear coverage supplied by other methods. As noted in Section 2.1, this area coverage may be important as information supplementary to the profile data obtained. In addition, an airborne system allows the investigation of areas which would be difficult to reach by ground-contact methods.

The cost of developing a suitable system and the cost of operation per mile of data appears to be high. Furthermore, the method requires the use of highly-trained personnel. The attainable accuracy would also be unsatisfactory except at such low altitudes that a helicopter would be required. Another source of error is the fact that vegetation or snow might mask the elevation of the ground, allowing an indication of only the top of the ground cover. Since the surface of snow is generally devoid of visible detail, it is not clear that stereo methods could be used at all. Finally, variations in absolute altitude of the aircraft could introduce appreciable discrepancies into the profile measurements.

3.2.3.2 Sonic Altimeters

The sonic altimeter, as developed for indication of relative height of an aircraft above the ground (Ref. 18), represents a principle which might be adapted to terrain measurement. Several devices have been developed for the purpose of aircraft height measurement, all using the same basic principle of measuring the time required for a sound pulse generated in the aircraft to reach the earth and be reflected back to a microphone in the aircraft. A large number of mechanizations of this principle have been developed, differing mainly in the type of components used for the various steps in the operation. Data on accuracy indicate that for some of the systems the error in height measurement could be held to a range of plus or minus one foot.

It is difficult to determine the ultimate capabilities of such a system for terrain measurement purposes without experimentation; however, some idea can be gained of the problems involved. One problem is to reduce the range of error of vertical measurement to less than plus or minus one foot. Such accuracy would probably be attainable, since an underwater sound-ranging device with an error of only three inches has been reported (Ref. 19). Such accuracy in water implies that the error in air could be kept to less than one inch, because of the lower velocity of sound in air as compared to water.

Sonic methods can be used only if the area from which the sound beam is reflected can be held within the horizontal resolution required of the terrain measuring system, i.e., one foot square or less. In order to obtain this resolution, a highly directive sound source and sound pickup must be used, which can best be achieved at ultrasonic frequencies. For example, a sound source whose radiating diaphragm has a diameter of 10 times the wave length of the sound produces a beam in which the energy intensity at the center is twice the energy intensity radiated along a cone whose half angle is 2.5 degrees. An increase in over-all directivity can be obtained by using a sound pickup having the same general dimensions. For a sound frequency of 20 kc, the wave length is roughly 0.06 feet, so that a diaphragm of 10 wave lengths would have a diameter of only 0.6 feet. It would therefore apparently be necessary to fly the aircraft at less than 20 feet above the ground to maintain satisfactory horizontal resolution and to offset the high absorption rate of sound energy at ultrasonic frequencies. Measurements from such a low altitude could only be made by helicopter.

Thus, although the development of a terrain measuring system based on the principle of sonic reflection might be possible, it would offer some serious developmental and operational problems.

3.2.3.3 Radar Altimeters

Radar has been used in a number of devices for indicating the altitude of an aircraft with respect to the ground below it. In at least one case the purpose of the device is similar to that of the terrain meter, namely, to record a continuous profile of the ground directly under and along the path of an airplane in flight (Ref. 20). However, the margin of error of this device as well as of any other radar device is far greater than that permitted by the requirements stated in Section 2.2. For example, the airborne profile recorder described in Reference 20 has a margin of error of plus or minus 20 feet over land.

Other methods of distance measurement by electrical or electromagnetic means have been noted in the literature. An aircraft altimeter making use of the measurement of capacitance to ground has been developed, and a radar system making use of visible light has been reported. However, with none of these methods does it seem possible to achieve the necessary accuracy or convenience of operation.

3.2.4 Comparison of Methods

Hand-carried systems of profile measurement are comparatively slow but are quite accurate and are suitable for difficult country. Vehicular systems operate at considerably higher speeds and, by proper choice of type of vehicle, should be able to negotiate most, if not all, terrain of interest. In both of these cases, the route followed by the measuring equipment could be similar to the route followed by a military vehicle. The accuracy of the hand-carried systems and the slope integration system appears acceptable, but this must be verified by further analysis and experiment. Airborne systems operate independently of terrain conditions and can operate at high rates of speed. However, the accuracy obtainable from these systems is generally less than that required in terrain measurement. The accuracy may be further decreased by vegetation or snow covering the ground area being measured. Error may also be introduced through undetected variations from a constant altitude in the flight path of the aircraft. Finally, for some systems there is a serious problem of achieving fine area resolution.

It is therefore concluded that the only methods which show any promise are conventional surveying methods, a hydrostatic leveling system, and the slope integration method. The specially designed hydrostatic system discussed in Section 3.2.1.2 is considered preferable to conventional surveying methods because it would permit faster and easier operation. Such a system could be developed at small cost. As compared to the hydrostatic system, the slope integration system requires a considerably greater initial development cost. But once developed, it should be capable of much greater operational speed (by an estimated factor of 30) and hence could be operated at lower cost. Its accuracy of elevation measurement is expected to be within the stated requirements, and a much greater degree of continuous horizontal resolution could easily be obtained than would be feasible with the hydrostatic system. The laboratory equipment and methods required for data reduction would probably be quite similar for both systems. Since the slope integration method makes use of a vehicle, no major design or operating change is required to include an automatic route recording device as part of the system.

On the basis of this comparison, it is concluded that the slope integration method provides the most suitable means of obtaining terrain profile data in substantial quantities.

IV

ANALYSIS OF SLOPE INTEGRATION METHOD

4.1 DATA PROCESSING SYSTEM ORGANIZATION

In the slope integration method of terrain geometry measurement, the measured data consist of some function of the pitch angle, θ, of a towed trailer, and the forward motion, s, of the trailer along the surface of the ground. In order to convert these measured quantities into the final output voltage representing y as a function of x, the data must be processed through several steps. The data processing system may be mechanized in a large variety of ways. However, before the advantages and disadvantages of the various methods can be pointed out, it is necessary to describe the basic operations performed by the system, without indicating the specific types of equipment to be used.

Elevation data can be handled in the system either in the form of y, the elevation itself, or as dy/dx, the rate of change of elevation with respect to horizontal distance. If data were processed as elevation itself rather than elevation rate, a data-processing system of high resolution would be required to deal with data from hilly country where the total range in elevation is large compared with the allowable vertical measurement error of one or two inches required for the short wave length components. Since economical methods of recording and computing necessarily have limited accuracies, it is preferable to work with elevation rate rather than elevation until the final step in the process is reached. However, even when dealing with dy/dx instead of y, good instrumentation accuracy will be required.

As shown in Figure 4.1-1, the field equipment consists of an angular reference device providing continuous pitch angle data, an odometer providing distance indication, and a recording device capable of making a continuous record of these data, although not necessarily in their original form.

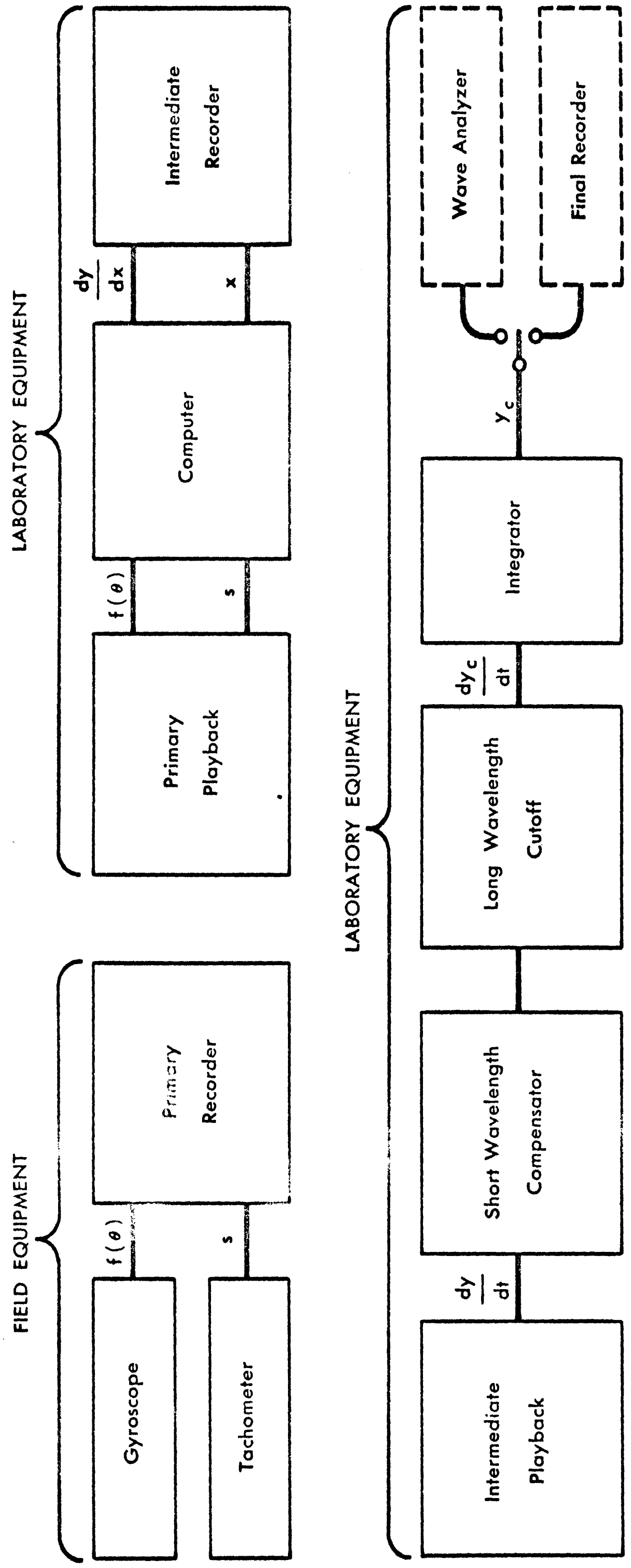

FIG. 4.1-1 FUNCTIONAL DIAGRAM OF TERRAIN DATA MEASURING SYSTEM

Because it is most convenient to use analog computer equipment of a type capable of performing integration only with respect to time, the original record must be converted in the laboratory to such a form that, for constant horizontal velocity, dx/dt, an analog voltage can be produced which is proportional to dy/dt. This requires an intermediate record in which distance along the record is proportional to x, the horizontal component of distance along the ground. If this record is played back at a constant speed, i.e.,

$$\frac{dx}{dt} = k \quad , \tag{4-1}$$

and if the recorded quantity is dy/dx, then the output voltage will be

$$\frac{dy}{dx} = \frac{dy/dt}{dx/dt} = \frac{1}{k} \cdot \frac{dy}{dt} \quad , \tag{4-2}$$

the form desired. By definition, the quantity dy/dx is equal to tan θ. The quantity x, required to control the position of the intermediate recording medium during the recording process, can be obtained by mechanizing Equation 3-2.

The analog voltage obtained from the intermediate recorder is first passed through a "short-wave-length compensator," the function of which is to correct for deficiencies in the representation of ground wave components of wave length close to the measuring wheelbase length (Sec. 4.3).

The difficulty, previously discussed, of obtaining an accurate record of elevation as a function of horizontal distance can be eliminated if the large excursions of elevation are eliminated. Since these large excursions are primarily at long wave lengths beyond the range of interest, they may be eliminated from the profile data record by a "long-wave-length cutoff filter," which attenuates sinusoidal components greater than a certain wave length, such as 100 feet. Therefore, the signal is passed through such a filter to produce dy_c/dt, the compensated value of rate of change of elevation. This signal is then routed through an integrator to convert elevation rate dy_c/dt, to elevation, y_c. This voltage, representing elevation for a constant value of dx/dt, is the output of the terrain measuring system in a form suitable for use in a harmonic wave analyzer or in the preparation of a final record to be used in an analog computer.

4.2 DESIGN CONSIDERATIONS

In order to perform the functions described above, a variety of methods and equipment might be used. The design considerations to be taken into account in arriving at a choice of the best method of mechanization will now be discussed briefly.

The angular reference device might take one of several forms. An active pendulous system, such as that used in the Johnson Elevation Meter, is one possibility; and a vertical gyro, such as is used in aircraft attitude indicating systems, is another. Both devices are considered capable of providing adequate accuracy for the present purpose. The gyroscope, however, has the advantage that by minor modifications of the electrical pick-off system, pitch data in terms of the angle itself or as one or more trigonometric or arbitrary functions of the angle can be obtained.

A choice is available in the form of the data obtained from the odometer. This could be either a voltage proportional to the surface velocity, v, or could be a succession of pulses corresponding with constant increments, Δs, along the ground.

Determination of the design of the recording equipment rests upon three choices that must be made concerning different aspects of the equipment:

1. Should separate primary and intermediate recorders or a single combination recorder be used?

Figure 4.1-1 illustrates the primary and intermediate recorders as separate components, one as a part of the field equipment, the other as a part of the laboratory equipment. The alternative design would eliminate the primary recorder, so that the outputs from the gyroscope and the odometer would be fed directly into the computer, the resultant computations then passing to the intermediate recorder. Thus the computer and the intermediate recorder would be included in the field equipment.

Although the alternative design would create the undesirable condition that a considerably larger amount of equipment would be necessary in the field, this design would minimize the total amount of equipment needed and would also make less likely the deterioration of the data.

2. Should digital or analog records be made?

Digital methods of data handling are capable of providing any required degree of accuracy, depending on the complexity of the system chosen. Analog methods of data handling are generally less complex than digital methods but are limited in attainable accuracy. If digital recording and processing methods are used, the output of the measuring devices must be converted to digital form and then reconverted to analog form at the point at which the data are played back from the intermediate recorder.

3. Should photographic film, magnetic tape, or perforated paper tape be used as the recording medium?

A photographic film recording system in which the face of an oscilloscope is photographed by a strip camera would be less expensive in first cost but would require considerable quantities of film. Magnetic tape recorders, widely used in data recording systems, are rugged and dependable, although somewhat expensive. A perforated paper tape system, for which the method of recording is inherently digital, is inexpensive and reliable.

In choosing among these three methods for the intermediate recording process, the major consideration is that both the photographic film and magnetic tape systems must be servo-driven so that the velocity corresponds to $v \cos \theta$ at all instants. This is an unusual requirement for either type of system and would involve the modification of commercially available equipment. In addition, severe problems arise in obtaining reliable and accurate control of the drive-motor speed. Nevertheless, these methods were considered carefully because of their basic simplicity. A servo-drive is not necessary when perforated paper tape is used.

The remaining components in the data measuring system present no serious design problems. The short wave length compensation and the long wave length cutoff filters shown in Figure 4.2-1 are simple frequency selective electrical circuits. The integrator can be a conventional operational amplifier. The components should present no serious design problems.

4.3 ALTERNATIVE METHODS OF MECHANIZATION

A number of possible mechanizations of the terrain measuring system were studied, of which three types were given special consideration:

1. A system using a vehicle-mounted magnetic recorder as the intermediate recording device. The quantity tan θ would be recorded in analog form, the tape speed being servo-controlled to correspond to v cos θ. An alternative to this method would use photographic recording.
2. A system using separate primary and intermediate recorders. The primary recorder would produce a magnetic record, using frequency-modulation techniques, of the quantities v sin θ and v cos θ in analog form. In the laboratory these quantities would be played back as analog voltages, and a combination analog and digital data-processing system would produce values of Δy for constant Δx to form the intermediate record on punched paper tape.
3. A system producing a primary record of θ in digital form on magnetic or perforated tape. This would be coded in such a way that the tape playback could be made directly into an already available digital computer. The computer would produce an intermediate record on perforated paper tape of Δy vs. Δx, the same form as described for the second type of system.

A comparison of the advantages and disadvantages of the above methods has resulted in the choice of the third method for the following reasons:

1. The development and use of special circuitry is minimized.
2. The processing of the data between the primary and intermediate recorders introduces no appreciable errors.
3. The amount of equipment which must be carried aboard the measurement vehicle is kept reasonably close to the desirable minimum.

4. The system is adaptable to different modes of operation. In particular, the accuracy and speed of primary data collection may be varied without major modifications of the basic equipment. Also, it is comparatively simple to add to the basic system certain items of equipment which permit a reduction of the amount of vehicle-borne equipment at the expense of some increase in over-all complexity, and which eliminate the need for the digital computer if a greater percentage of error is permissible.

A detailed description of the selected method is given in Section 5.1.

4.4 ACCURACY STUDIES

To provide a basis for making certain decisions concerning the design of the measuring system, an analysis was made of certain aspects of the system accuracy problem.

The accuracy attainable with the slope integration method will be limited by the following types of errors which occur:

1. Errors in measurement of slope due to the size of the measuring wheelbase.

2. Errors due to the failure of the measuring wheels to follow the ground profile. Errors of this type may occur if the soil is unevenly compacted; if the wheels contain soft material (such as rubber) which may deflect; if the rear wheel does not follow the same track as the front wheel; if the wheels leave the ground due to excessive speed; or if the wheel to which the odometer is attached slips with respect to the ground. Although the magnitude of these errors can be determined only by experiment, the high over-all accuracy reported for the Johnson Elevation Meter (1 foot in 1 mile) indicates that these sources of error may not be excessive in the present application.

3. Errors due to limitations of the instrumentation, recording, and data reduction devices. The magnitude of errors of this type can be limited by proper choice of components, by minimizing the number of steps in the data reduction process, and by using digital rather than analog methods of handling the data.

An analysis of the first type of error is presented in Section 4.4.1. The effect of all three types of errors in slope measurement on final results is discussed in Section 4.4.2.

4.4.1 Errors Due to Finite Size of Wheelbase

In mechanizing Equation 3-1, the incremental distance, ds, is obtained from an odometer attached to the front measuring wheel and is therefore a measure of the distance which the front wheel has moved along the ground surface (Fig. 4.4-1). The angle of the ground immediately under the front wheel, θ_g, should be used for the integration. The measurement actually recorded is θ_w, the inclination of the line between the two wheels. The latter angle can differ appreciably from the slope of the ground under the first wheel.

An indication of the magnitude of this effect was obtained by recording graphically a 12-inches high by 12-inches wide obstacle. The results are shown in Figure 4.4-2. The three curves show the representation of this obstacle as determined by measuring assemblies of different wheelbase length. As expected, the representation is improved by reducing the wheelbase. All values result in reasonably accurate indications of total height of the obstacle, but in each case a longitudinal shift in position and a distortion of the vertical slopes of the obstacle are introduced. Furthermore, the elevation after crossing the obstacle differs from that ahead of the obstacle. Since this analysis was graphical, some of the observed errors between the elevation of the real and measured obstacle possibly resulted from errors in graphical construction.

An analysis was made to determine the accuracy of measuring sinusoidal ground waves. The simplifying assumption was made that the amplitude of the ground wave is small compared to the diameter of the

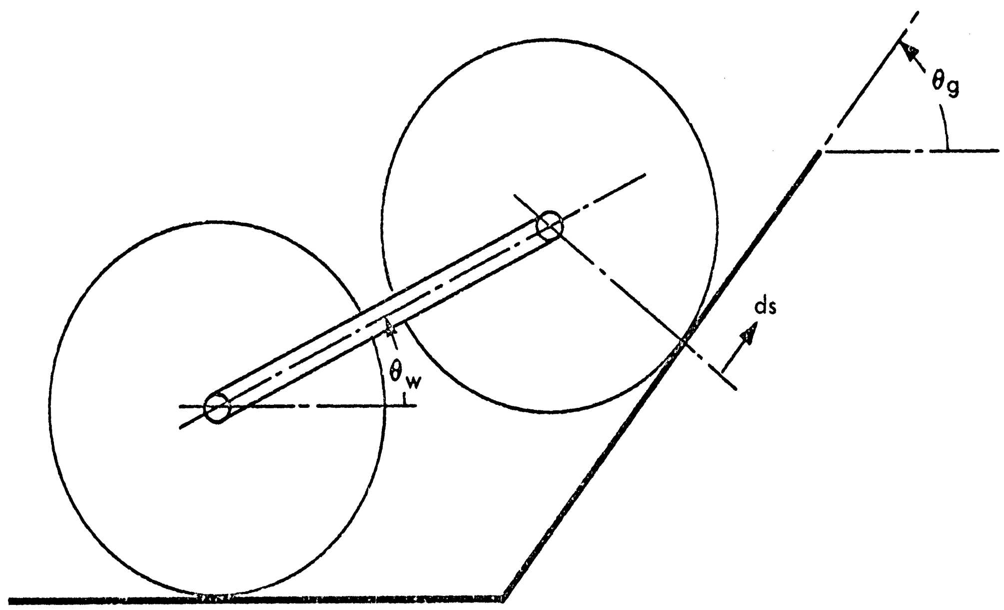

FIG. 4.4-1 MEASUREMENT GEOMETRY

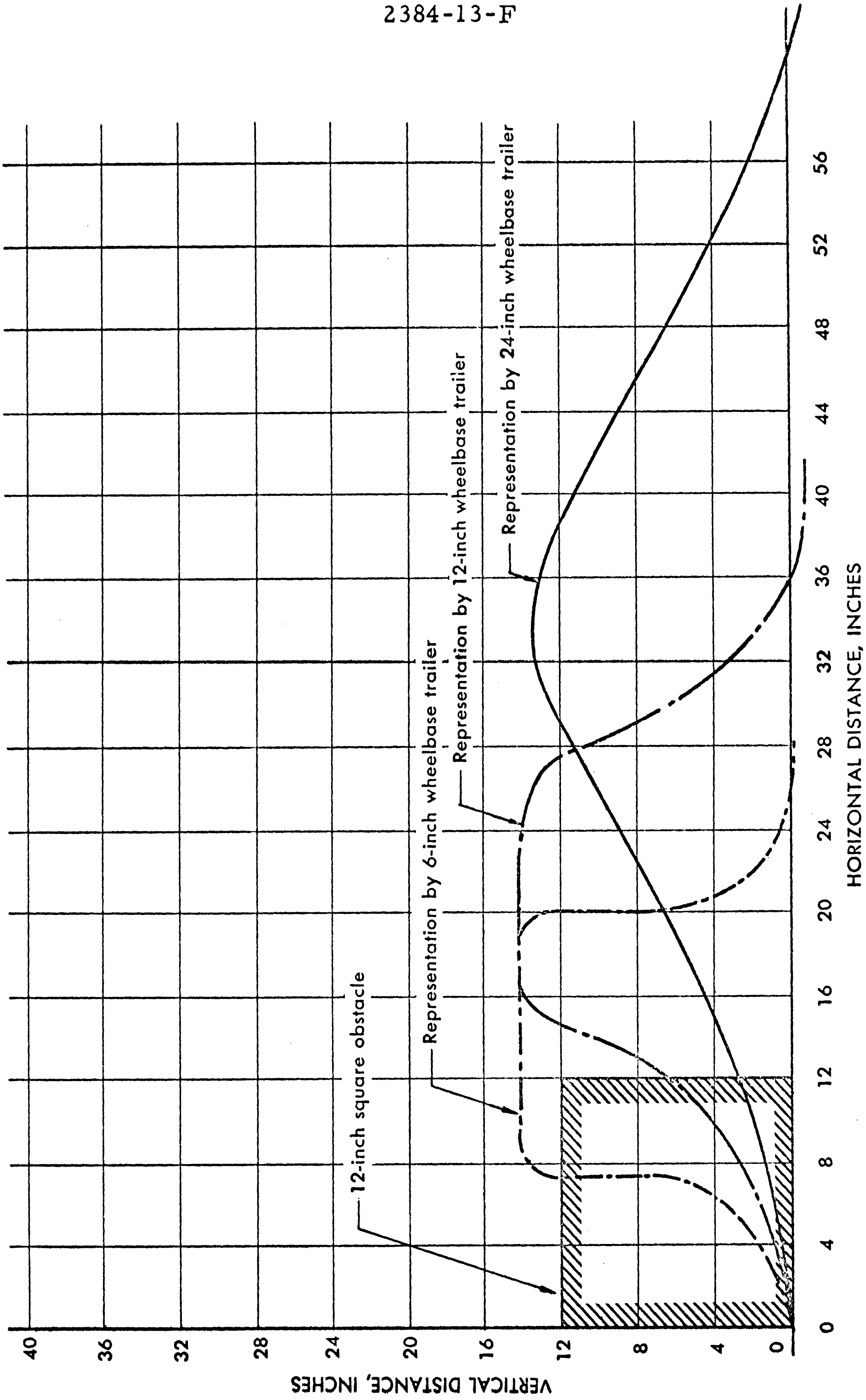

FIG. 4.4-2 MEASUREMENT OF SQUARE OBSTACLE

measuring wheel. The results are shown by the solid line in Figure 4.4-3. They indicate that the trailer will reproduce the amplitude of a sinusoidal ground wave with less then 10 per cent error for wave lengths of more than about four wheelbase lengths. For shorter wave lengths, the error increases rapidly. For example, if the wave length is equal to the wheelbase, the difference of height of the front trailer wheel with respect to the rear is always zero, and the system registers zero amplitude. In the measurement of a complex ground wave containing sinusoidal components of many wave lengths, it is possible to correct to some extent for the errors by passing the measured data through electrical compensating networks which emphasize the amplitude of the components having wave lengths which are close to the wheelbase. The dashed line in Figure 4.4-3 shows how such a filter could keep the errors in sinusoidal measurement to less than 10 per cent for all wave lengths except those close to the wheelbase of the trailer.

It should be noted that the type of inaccuracy discussed above is not peculiar to the slope integration method, but is inherent in any measuring system having a finite horizontal resolution.

4.4.2 Effect of Errors in Measurement of Pitch

The following brief analysis provides some idea of the required accuracy of individual readings of θ. Section 2.2 points out that systematic errors have no significance in terrain measurement. It is therefore permissible to consider only random measurement errors. It will be assumed that these have a Gaussian distribution. The majority of individual readings of θ will be small enough that θ can be assumed equal to $\sin\theta$ and $\cos\theta$ equal to 1.

The total change in elevation over a distance x is

$$y - y_0 = \sum_{i=1}^{n} \theta_i \, \Delta x \quad , \qquad (4\text{-}3)$$

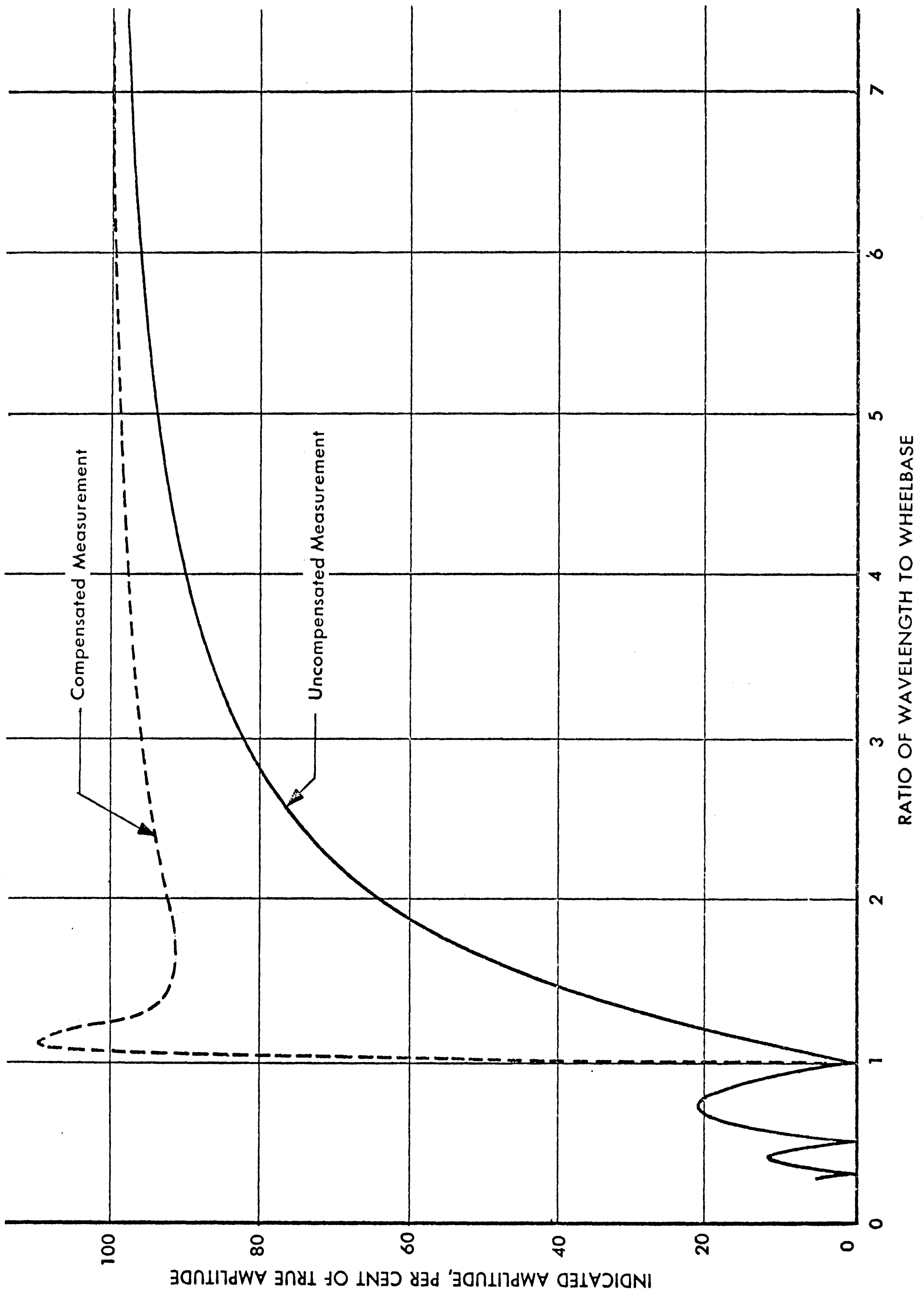

FIG. 4.4-3 MEASUREMENT OF SINUSOIDAL GROUND WAVES

in which θ_i is the individual reading, Δx is the increment of horizontal distance per reading, and n is equal to $x/\Delta x$. The standard deviation of the total error of n readings is

$$\sigma_t = \sigma \sqrt{n} \ , \qquad (4-4)$$

in which σ is the standard deviation of the individual values of $\theta_i \Delta x$, and the error in each reading is uncorrelated with the errors in the other readings. If a reading were taken every 2 inches with a standard deviation of θ_i equal to 4 degrees (0.07 radians), σ would be 0.14 inches. For a total measurement length of 10 feet (120 inches), n is 60 and σ_t has a value of $0.14 \sqrt{60}$ or 1.08 inches. For a total measurement length of 100 feet (1200 inches), σ_t has a value of 3.42 inches.

The interpretation of the above analysis on the basis of a Gaussian distribution for $y - y_0$, is that if 68 per cent of individual measurements of θ lie within $\pm$ 4 degrees, then 68 per cent of all 10-foot runs would result in accumulated errors in the range of $\pm$ 1.08 inches, and 95 per cent of 10-foot runs would result in accumulated errors in the range of $\pm$ 2.16 inches. Similarly, 68 per cent of 100-foot runs would result in accumulated errors in the range of $\pm$ 3.42 inches, and 95 per cent of 100-foot runs would result in accumulated errors in the range of $\pm$ 6.84 inches. These are roughly the values of the allowable errors mentioned in Section 2.2.

The standard deviation of 4 degrees for θ represents the accumulation of both mechanical errors and data-processing errors. Although the figure of 4 degrees for the standard deviation of these errors furnishes a design objective, the capability of a given system design for meeting this objective cannot be determined analytically because of the uncertainty of the performance of the mechanical portions of the system. The design figure can, however, provide a basis for assumptions of allowable errors in the data-processing system. For example, if the value of θ is recorded digitally, it is possible to estimate the resolution required of the digital representation. If a total range of 180 degrees is represented by a seven-bit number, then the least significant binary digit corresponds to $180/2^7$ or 1.4 degrees. The standard deviation due to rounding off the value is 28.87 per cent of the last place retained, or 0.4 degree. This is small compared to the total allowable value of 4.0 degrees.

V

PROPOSED EXPERIMENTAL PROGRAM

Before an attempt can be made to design the prototype of the terrain measuring system which will provide the best performance in terms of speed, accuracy, and reliability, an experimental system must be constructed and tested, and certain supplementary system analyses must be completed. This section outlines the proposed experimental program and describes the experimental model.

The program outlined in this section requires the performance of the following tasks:

1. detailed design and construction of an experimental terrain measuring system,
2. test of the system to determine required modifications and optimum adjustment, and to determine performance capabilities,
3. conduct of additional design studies and operational analyses to produce a firm basis for the design of a prototype system,
4. preliminary design of a prototype system.

5.1 PRELIMINARY DESIGN OF EXPERIMENTAL SYSTEM

It is not within the scope of this report to give complete design details of the experimental system, but merely to indicate its basic organization and certain important design parameters. The circuits and components described in this section are all of conventional design. For those components or circuits which are commercially available, a specific item which may be purchased from the manufacturer is usually indicated. Each item is considered suitable for the purpose but is not necessarily the only type which might be used.

In addition to those components which are to be specifically provided as integral parts of the terrain measuring system, certain items are considered to be available as government-furnished equipment or on a rental basis; in particular, among such items are the vehicle used for towing the measuring trailer and the digital computer equipment used in the data reduction process.

5.1.1 Mechanical Design of Field Equipment

The slope integration method requires that continuous measurements be made of the slope and the surface travel of a short wheelbase trailer which is moved over the ground being measured. The frontispiece shows a view of the field equipment assembly for performing this operation.

5.1.1.1 Towing Vehicle

The towing vehicle should be a wheeled vehicle designed for both cross-country and highway operation. In particular, it should have four-wheel drive and a large minimum clearance above ground. There should be an enclosed area in the rear of the vehicle which will hold the primary electrical instrumentation equipment and auxiliary devices (such as power supply, test equipment, and spare components), and which will accommodate an operator.

It is unlikely that any single vehicle type would meet all the above requirements or be suitable for all terrain types and conditions. The 3/4-ton 4 X 4 ambulance truck M43 is recommended as the most suitable existing type (Ref. 21). This truck is shown in the frontispiece, and pertinent data about it are tabulated in Table 5-1.

5.1.1.2 Trailer

The trailer which carries the primary instrumentation devices of the system is shown in Figure 5.1-1. It is attached to the towing vehicle by a conventional trailer hitch. The trailer chassis is supported by a suspension system on two automobile wheels of standard size. The measuring assembly is attached to the trailer suspension system by a pivoted support which allows the assembly to rotate in yaw. The slope of the ground is sensed by a pair of 11-inch diameter wheels mounted in tandem on a 12-inch wheelbase at the rear end of the assembly. An electrical contactor mounted on the leading wheel produces a voltage pulse at

TABLE 5-1

DATA ON AMBULANCE TRUCK M43

Dimensions:	
Height	7 ft 7-7/8 in.
Length	16 ft 6-3/4 in.
Width	6 ft 1-1/2 in.
Wheelbase	126 in.
Weight:	
Net	7,150 lb
Payload	1,400 lb
Gross	8,550 lb
Recommended towed load (max.):	
Cross-country	4,000 lb
Highway	6,000 lb
Engine	Dodge Model T245
Engine horsepower:	
At 1,600 rpm	57 brake hp
At 3,400 rpm	94 brake hp
Fuel consumption (loaded) (approx.)	9 mpg
Cruising range (loaded)	225 mi.
Transmission: Helical gear, synchro-shift unit, with four forward speeds and one reverse.	
Electrical system	2 batteries, 24-volt total
Ground clearance	10-3/4 in.
Angle of approach	47°
Angle of departure	32°
Fording depth (max.):	
Without fording kit	42 in.
With fording kit	84 in.
Grade ascending ability (max.) limited by traction	68 per cent
Turning circle (diam.) right or left (min.)	50 ft

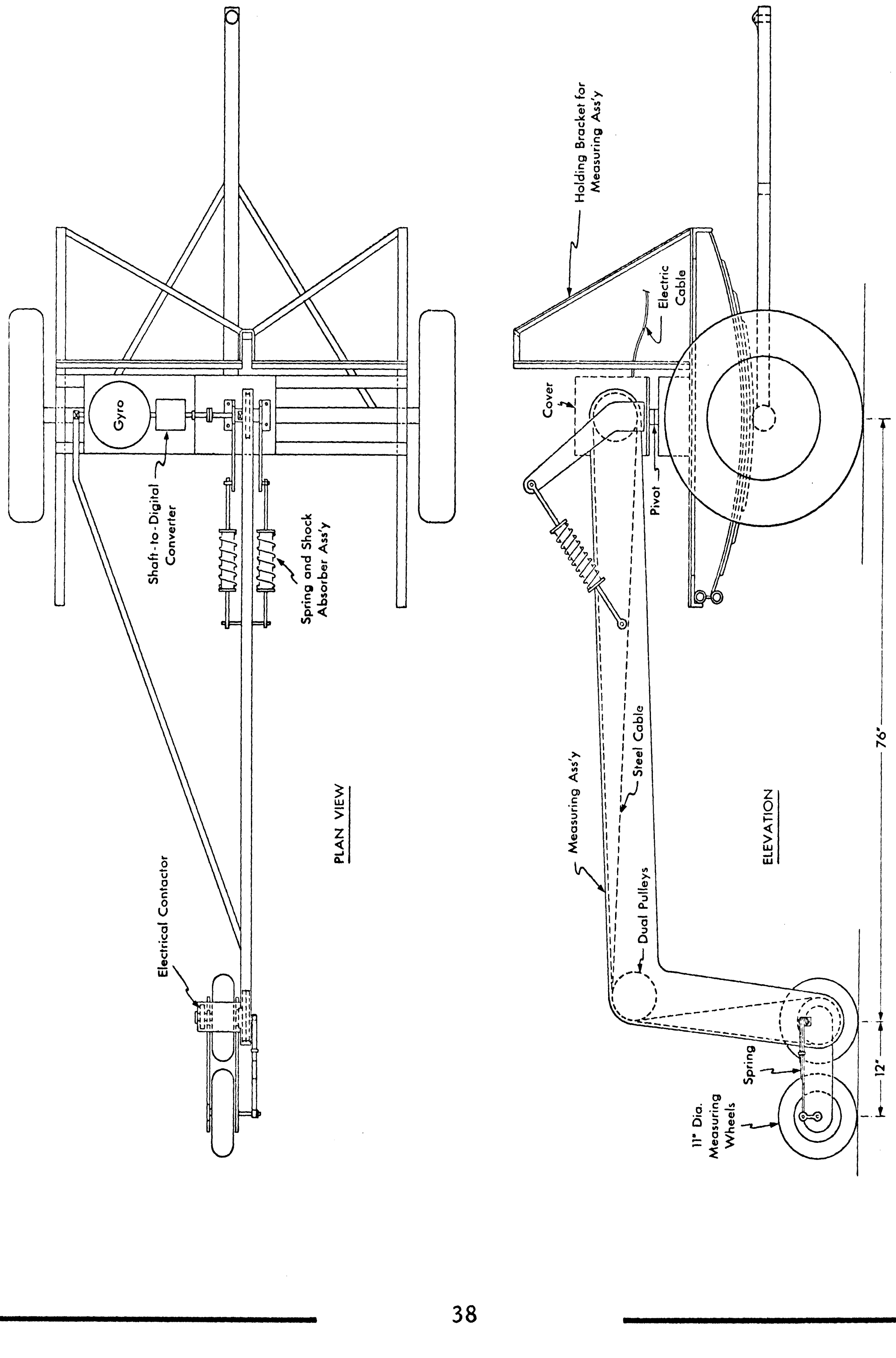

FIG. 5.1-1 TRAILER ASSEMBLY

2-inch increments of s, the travel of the wheel along the surface of the ground. The pitch angle of the measuring wheels is measured by a vertical gyroscope mounted on the pivoted platform of the measuring assembly, the total allowable range of pitch angle being from -90 to +90 degrees. Attached to the outer gimbal shaft of the gyro is the shaft of a photoconductive type of shaft-position-to-digital converter, such as that described in Reference 22. The body of this device is linked mechanically to the measuring wheels so that it produces a digitally-coded representation of θ, the angle of the wheelbase with respect to the vertical. Seven binary digits are provided for, corresponding to a resolution of 1 part in 128 over a total angle of 180 degrees.

The tendency of the wheels to leave the ground is minimized by providing a spring to hold the measuring assembly down and a damping device (probably acting with most effect on extension) to damp out vibrations. The effectiveness of spring and damper is increased by keeping to a minimum the pitch moment of inertia of the assembly about its point of attachment to the pivoted platform. This is done by making the framework of aluminum and by locating the gyro at the point of attachment rather than on the wheel assembly. This gyro location also serves to reduce the road shock to which the gyro is subjected. A second spring is attached to the measuring wheels themselves to keep the rear wheel on the ground. Provision is made for adjusting both the spacing of the wheels and the values of the spring and damping rates to obtain the best design. The tires are made of solid rubber to provide some protection against shock while minimizing errors due to rubber deflection, and are treaded to increase traction. For convenience in traveling from one measurement area to another, the measuring assembly can be raised off the ground and held in a vertical position by an over-center spring arrangement and a holding bracket.

5.1.2 Data-Processing System

The proposed data-processing system is shown in Figure 5.1-2. Equipment shown by dotted lines is assumed to be available without being an integral part of the system. The photoconductive type of shaft-position-to-digital converter (Ref. 22) is mechanically attached to the gyroscope and trailer frame so that the angle of the converter shaft with respect to

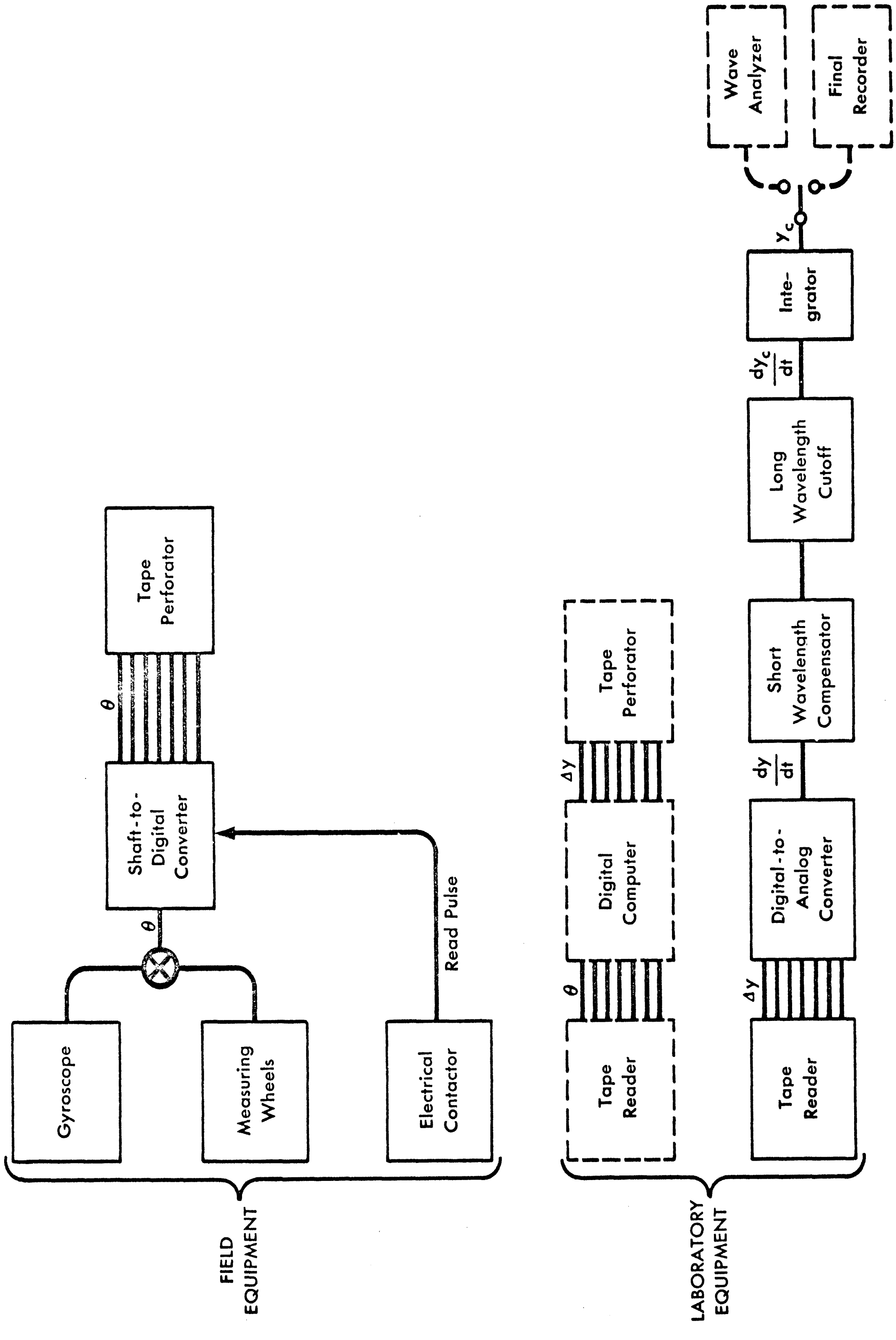

FIG. 5.1-2 FUNCTIONAL DIAGRAM OF DATA-PROCESSING SYSTEM

its body is always equal to θ. In the converter, a code wheel attached to the output shaft has a pattern of transparent and opaque areas which respectively transmit and absorb light generated in pulses by a gas discharge lamp. This light is channeled through an arrangement of slits so that it falls on a series of photoconductive cells. For a specific angular position of the shaft, the pattern of illuminated and nonilluminated cells represents the angle in a cyclically-permuted binary code (Fig. 5.1-3). This code, related to the normal binary code, has the advantage that adjacent numbers, which differ only by the binary digit in one position, can be read off the code wheel without ambiguity at the points at which the value of the quantity is changing. In operation, a pulse of current is passed through the lamp whenever a circuit is completed through the electrical contactor mounted on the leading wheel of the trailer. The current pulse occurs at constant increments of advance of the wheel along the surface of the ground.

The set of pulses produced by the photoconductive cells is routed to a tape perforating system, such as that manufactured by Teletype Corporation (Ref. 23). In this system, a set of thyratrons, one for each digit, acts as a receiving storage register. The pattern of conducting and nonconducting tubes in the storage register corresponds with the pattern of pulses received from each of the photoconductive cells. A pulse received from a cell represents the digit 1 in the binary system. If no pulse is received, the digit 0 is represented. The digital value of θ is then transferred to a holding storage register in order that the receiving register may be cleared to accept the next seven-bit number or "character." The value of θ remains in the holding register until a tape perforator, operating at a reading speed of 60 characters per second, reaches a point in its cycle at which the digital character in the register can be punched into the tape. When this point is reached, a reset pulse produced by a contact on the tape perforator clears the holding register to receive the next character. The system is capable of accepting inputs at a rate close to 60 characters per second. The tape perforator punches and advances the tape only when a new character is available in the holding register. Because the advance of the paper tape is therefore proportional to the advance of the wheel along the ground, the tape becomes a record of θ vs. s. Both the storage register equipment and the tape perforator are commercially available as a complete system.

Angle (Deg.)	Corresponding Decimal Number $(= \frac{\theta + 90}{1.40})$	Equivalent Binary Number	Equivalent C. P. Binary Number
-88.6	1	0000001	0000001
-87.2	2	0000010	0000011
-85.8	3	0000011	0000010
-84.4	4	0000100	0000110
-2.8	62	0111110	0100001
-1.4	63	0111111	0100000
0	64	1000000	1100000
+1.4	65	1000001	1100001
+2.8	66	1000010	1100011
+85.8	125	1111101	1000011
+87.2	126	1111110	1000001
+88.6	127	1111111	1000000

FIG. 5.1-3 DESIGNATION OF ANGULAR INFORMATION IN BINARY CODE

After being returned to the laboratory, the information on the tape is introduced into a digital computer. If certain instruction data can be punched into the tape along with the values of θ, the output of the tape can be read directly into the computer. If this instruction data cannot be placed on the original tape record in the field, an additional processing step in the laboratory becomes necessary.

The digital computing equipment most likely to be considered for the terrain measurement system would be either the computer being installed at the Detroit Arsenal (a Datatron computer, manufactured by ElectroData Corporation, Pasadena, California, as described in Reference 24), or MIDAC, the digital computer located at the Willow Run Laboratories (Ref. 25). At the time of preparation of this report, no determination has been made of the exact methods of coding the problem.

The function of the digital computer is to accept the record of θ vs. s and convert it to a paper tape record of Δy vs. x, in which Δy is the change in elevation of the ground surface over the constant increment, Δx, which corresponds with the horizontal increment represented by each advance along the tape. To do this, the computer performs the following operations on each θ character, although not necessarily in the order indicated (Fig. 5.1-4):

1. reads in θ as a seven-bit character in the cyclically-permuted binary code;
2. converts the quantity to decimal or other code used by computer;
3. computes the quantities $\Delta x_n = \sin \theta_n \Delta s$ and $\Delta y_n = \cos \theta_n \Delta s$;
4. determines whether another increment of Δx has been completed within the interval, e.g., at Point (I+1);
5. if not, stores values of Δx_n and Δy_n;
6. if another increment of Δx has been completed, computes the value of y at this point by interpolation;
7. subtracts from this value of y the previously stored value of y at Point (I); the resulting quantity is Δy_i;

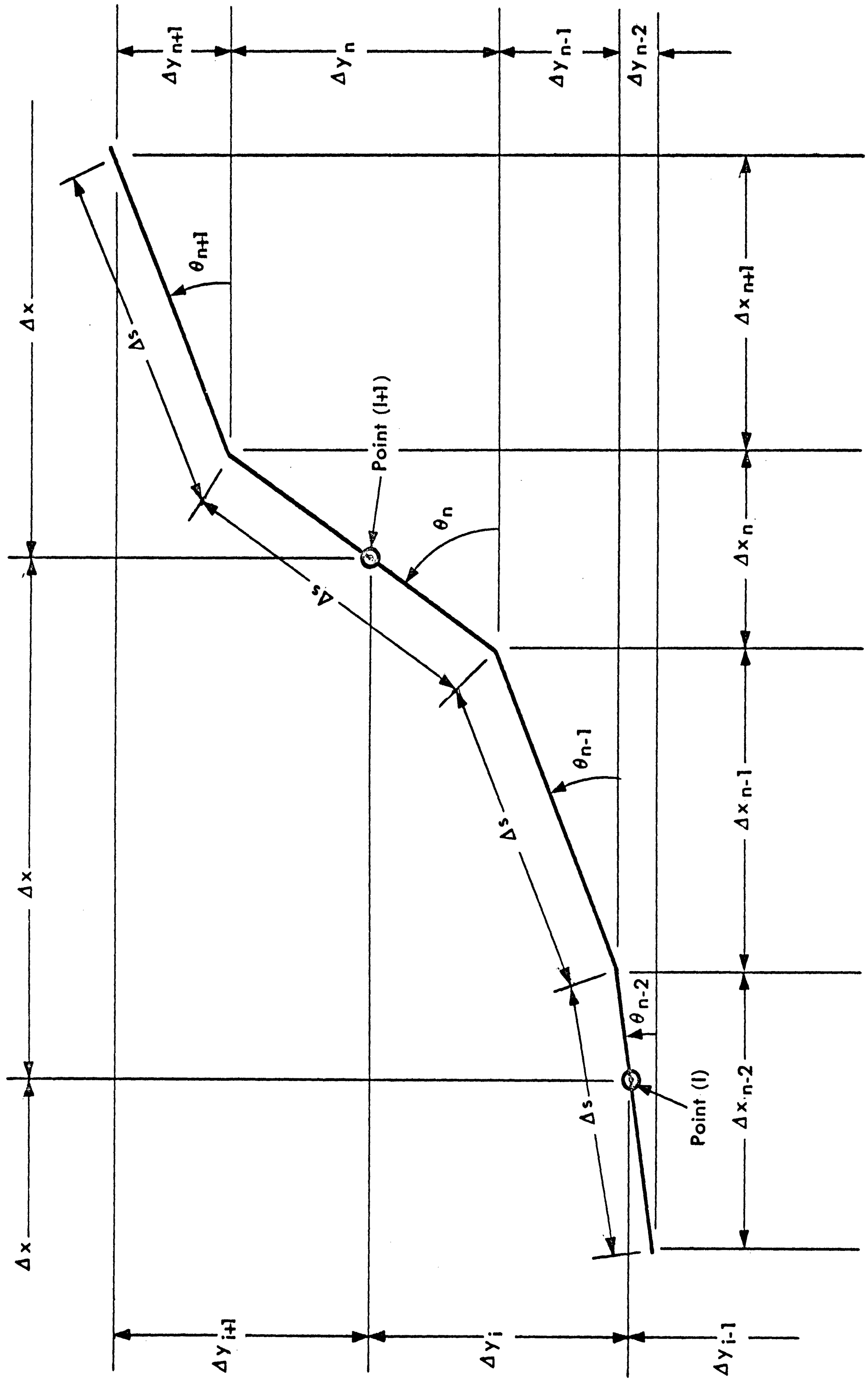

FIG. 5.1-4 GEOMETRICAL BASIS FOR DIGITAL COMPUTATION

8. converts this value of Δy_i to ordinary binary form;

9. prints out the binary character of Δy_i in a tape perforator similar to that used in obtaining the primary record. This paper tape now becomes the intermediate record of the process.

In the final steps of the process, the intermediate record is converted by a tape reader to a set of voltages representing Δy at a constant speed of tape advance, i.e., at constant dx/dt. Each set of voltages on the output wires of the tape reader is transmitted to a digital-to-analog converter whose function is to convert them to an analog voltage representing dy/dt. This voltage is then modified by frequency selective circuits to compensate for deficiencies in short wave lengths, to cut off components of long wave lengths, and to integrate the resulting record so that the elevation y_c is obtained.

5.1.3 Possible Modifications of the Data-Processing System

As stated in Section 4.3, the processing system just described can be adapted to other modes of operation by the addition of equipment sections at various points in the system. These modifications may be added to the system at a later time if the need for them becomes evident. Two modifications in particular will be discussed here.

5.1.3.1 Use of Alternate Recording Section

The first modification, shown in Figure 5.1-5, involves the use of a magnetic tape recorder. It has the advantage of reducing the amount of electronic equipment to be carried aboard the measuring vehicle, although the total amount of equipment in the system may be slightly increased and an additional processing step has been added. This step may also be necessary in order to facilitate the preparation of the paper tape record in a form suitable for direct introduction into a digital computer. This modification requires in the vehicle a single-channel magnetic-tape recorder of the direct recording type. The operation of this system is similar to that of the previously described system (Fig. 5.1-2) up to a point where the digital value of θ is used to set up a receiving register. For the modified system, this register consists of vacuum-tube flip-flops

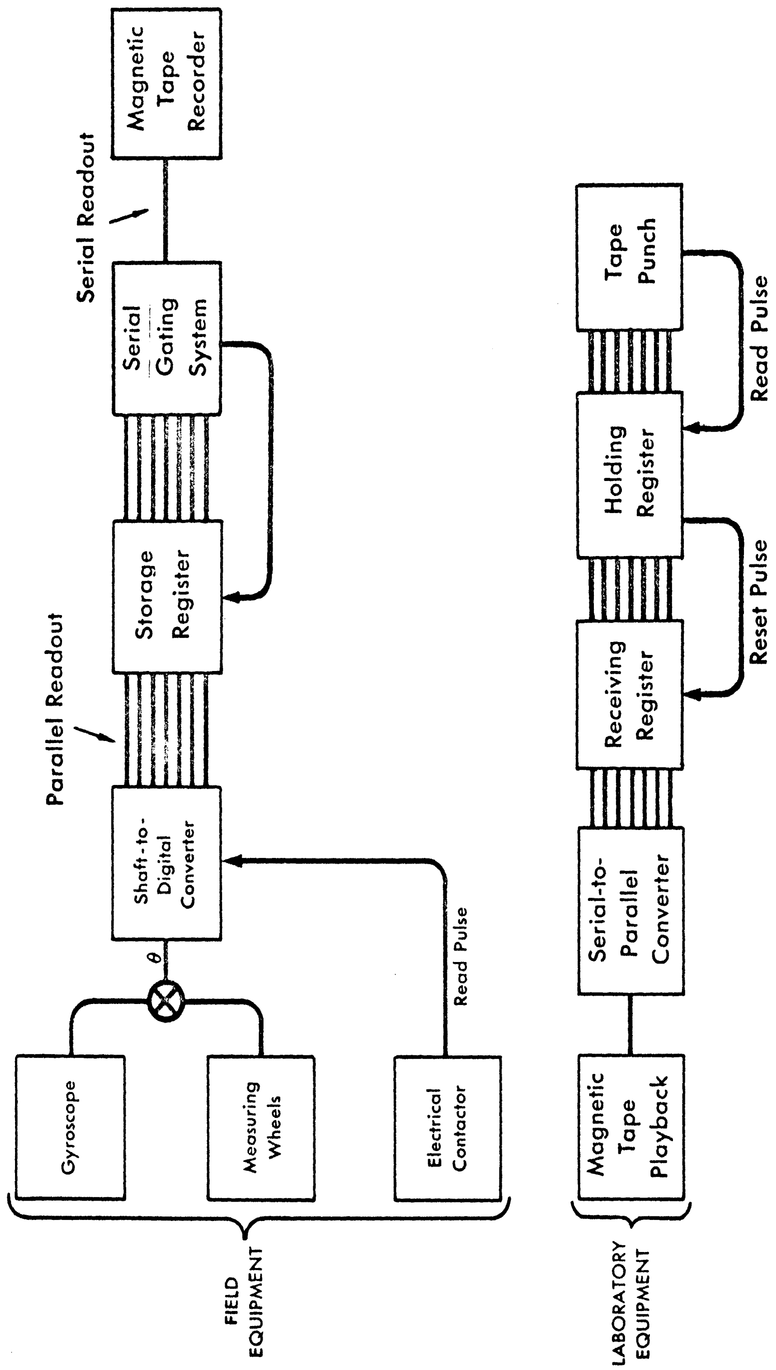

FIG. 5.1-5 FUNCTIONAL DIAGRAM OF ALTERNATE RECORDING SECTION

rather than thyratrons. By a suitable timing mechanism, these flip-flops are sampled sequentially, and a pulse or blank is produced on an output line in serial form, i.e., the instant at which each pulse or blank occurs corresponds to one position of a digit of the number. In addition to this output, a synchronizing pulse and a parity-checking pulse are fed to a tape recorder. When this record is played back in the laboratory, a serial-to-parallel converter, consisting of a timing circuit and a diode matrix, can be used to route the incoming pulses to the proper input terminals of the storage register of a tape perforating system.

It will be seen that this modification makes a two-step process of the primary recording. It is believed that this modification would bring about an appreciable reduction in the vehicle-carried equipment; but it is not recommended unless the experimental program indicates the importance of minimizing the complexity of the field system in order to increase reliability, or unless it is necessary to provide punched tape for direct input to a computer.

Another method of reducing the amount and increasing the reliability of field equipment would be to make use of magnetic core circuitry (Ref. 26). These techniques should be given careful consideration.

5.1.3.2 Use of Alternate Computing Section

The second modification to be discussed is shown in Figure 5.1-6. The purpose of this modification is to eliminate the necessity of using the digital computer to convert from the primary to the intermediate record. Firm estimates are not available as to the cost of data reduction by digital computer methods, but it appears that the cost might be in the neighborhood of $10 per mile. For large amounts of data reduction, it becomes more economical to develop and use a special purpose computer to replace the digital computer. Since this computer section requires additional development and since it reduces the accuracy of the results, it is recommended that digital computer reduction be considered until the necessity and feasibility of the alternate computing section are demonstrated.

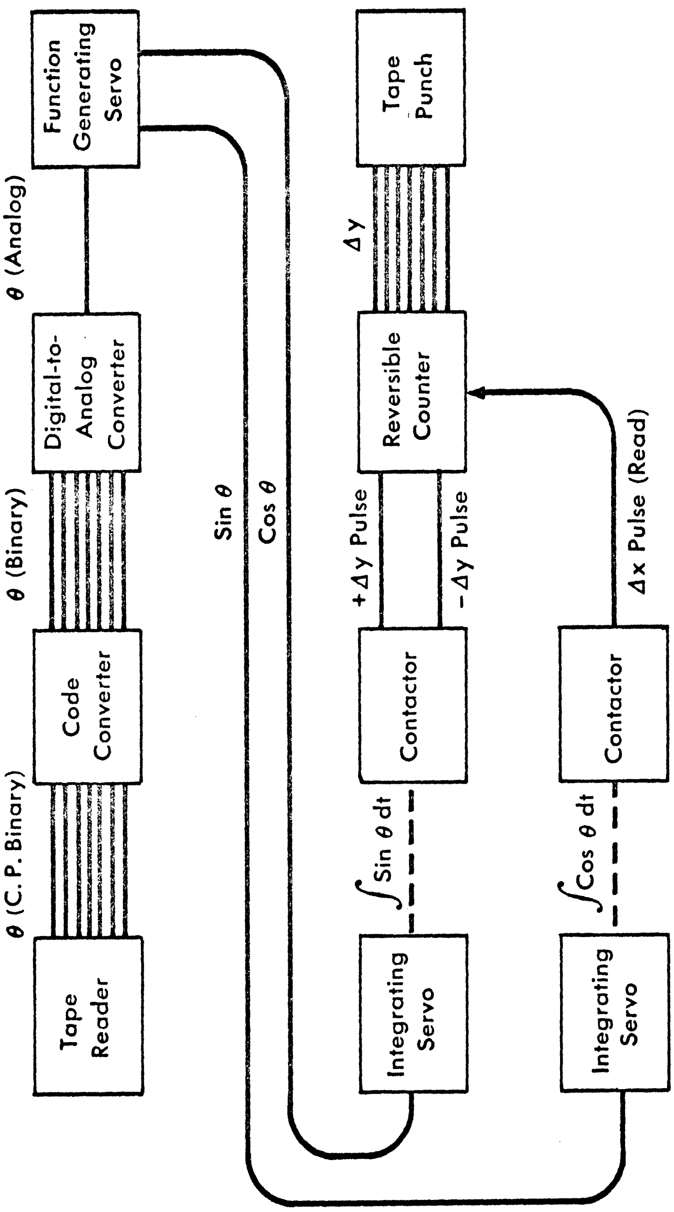

FIG. 5.1-6 FUNCTIONAL DIAGRAM OF ALTERNATE COMPUTING SECTION

In this alternate system, the digital representation of θ is fed back from the tape reader in the same way that it was for the digital computation process. The playback will, however, take place at a constant and much lower speed. The output of the tape reader represents the quantity θ in the cyclically-permuted binary code. First, it is therefore necessary to route this set of voltages to a code converter whose function is to produce from them a set of voltages representing the quantity θ in ordinary binary form. The output of the code converter is then introduced in parallel form to a digital-to-analog converter to obtain θ in analog form as a d-c voltage. By using this analog voltage to control a servomechanism, the shaft angle of the servo is made to correspond to the value of θ. Two potentiometers mounted on the output shaft of the servo have nonlinear windings designed to produce voltages corresponding to sin θ and cos θ respectively.

If the quantities sin θ and cos θ are now used as the inputs to two integrating servos, the velocity of the output shafts of these servos will be proportional to sin θ and cos θ respectively. Consequently, the shaft angles are proportional to $\int \sin \theta \, dt$ and $\int \cos \theta \, dt$. For a constant speed of operation of the tape reader, which corresponds to a constant speed of the measuring vehicle along the surface of the ground, the output shaft angles continuously represent the values of y and x for the advance of the measuring vehicle along the surface of the ground. By placing an electrical contactor on the output shaft of the cosine servo, a pulse can be obtained for constant increments of shaft angle, i.e., for constant increments of x motion. Similarly, a contactor located on the output shaft of the sine servo can produce pulses for constant increments of change of elevation. In the case of elevation, the increments can be either positive or negative; therefore, it is necessary to provide a contactor capable of producing pulses to represent both polarities. These $+\Delta y$ and $-\Delta y$ pulses are introduced into a reversible counter, so that the counter stores the total net change of y. Upon receiving a voltage pulse from the Δx contactor, the reversible counter feeds this net change of elevation into a tape perforating system of the type previously discussed; at the same time the reversible counter is reset to zero. Consequently, the reading in the counter at the time of receiving each Δx pulse corresponds to the total change of elevation encountered while the vehicle traversed the horizontal distance, Δx. The resulting punched tape therefore contains information of the same form as was produced by the digital computer.

5.2 PROPOSED TEST AND ANALYSIS PROGRAM

The experimental model described in Section 5.1 is to be tested to provide information upon which the design of a prototype model can be based. The test program and additional design studies of a detailed nature should be planned to produce answers to the following questions:

1. How should the mechanical design of the trailer assembly be adjusted or modified to give the greatest accuracy? In particular, values of wheel spacing and settings of each spring and damping device should be optimized.

2. What is the attainable forward velocity of the vehicle without excessive deterioration of system accuracy? The choice of a contactor pulse for each two inches of travel and a punched tape system handling 60 characters per second permits a maximum velocity of 10 feet per second. A more probable limiting factor will be the ability of the wheels to follow irregular ground at high speed.

3. What is the attainable accuracy of the over-all system? This should be determined for typical sections of cross-country terrain, and for artificial irregularities such as individual square or triangular obstacles.

4. Is the use of an alternate computing section, as described in Section 5.1.3, advisable? Can the seven-bit angular resolution and the two-inch horizontal resolution in the digital recording of θ be relaxed? The answer to these questions will depend on the expected quantity of measurements to be made and on the possibility of relaxing accuracy requirements.

5. What electrical component and circuit modifications are required to ensure a rugged, reliable field system? In particular, is the use of the alternate recording section discussed in Section 5.1.3 desirable?

6. What auxiliary data (e.g., plan view of route and physical characteristics of ground) should be collected and in what form?

7. What detailed arrangement of the data-coding is necessary in order to facilitate introducing the measured data into the digital computer?

8. What towing vehicle is recommended for the application? It is possible that a smaller vehicle than the 3/4-ton ambulance truck mentioned in Section 5.1.1.1 may be adequate.

5.3 ESTIMATED COST

The cost of carrying out the above program is estimated at $34,000. This includes the cost of personnel, purchased items, and travel, and provides allowance for overhead charges. No allowance has been made for the inclusion of the alternate recording and computing sections described in Section 5.1.3.

Estimated purchases are presented in Table 5-2. The estimates do not include the cost of the ambulance truck, since it is assumed that this vehicle would be available as government-furnished equipment. An allowance has been made for a small amount of digital computer time. However, this charge would be eliminated if a government-owned computer were available. The program would require a total of 15.0 man-months of engineering time and 8.0 man-months of technician time and would require 12 months to complete.

TABLE 5-2

ESTIMATED PURCHASES

Field Equipment		
Vertical gyro	1,200	
Shaft-to-digital converter	500	
Tape perforator control unit	1,400	
Tape perforator power supply unit	1,080	
High-speed tape perforator mechanism	866	
Gasoline-engine-driven generator	350	
Miscellaneous mechanical and electrical components	1,000	
Laboratory Equipment		
High-speed tape reader	645	
Digital-to-analog converter	1,300	
Two operational amplifiers plus power supply	1,100	
Miscellaneous mechanical and electrical components	100	
Use charge for digital computer	500	
Report supplies and printing costs	341	
Miscellaneous supplies and services	1,700	
Total purchases		12,082