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PROCEDURES FOR THE INTERPRETATION AND USE OF ELEVATION SCANNING LASER/MULTI-SENSOR DATA FOR SHORT RANGE HAZARD DETECTION AND AVOIDANCE FOR AN AUTONOMOUS PLANETARY ROVER

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ABSTRACT

To gather more information about the solar system, future missions to Mars should include visits to many remote locations on the planet surface for scientific experimentation. An autonomous roving science vehicle that relies on terrain data acquired by a hierarchy of sensors for navigation is one method of carrying out such a mission. Included in the hierarchy of sensors is a short range sensor with sufficient resolution to detect every possible obstacle and with the ability to make fast and reliable terrain characterizations. A multi-laser, multi-detector triangulation system is proposed as a short range sensor. The general system is studied to determine its perception capabilities and limitations. A specific rover and low resolution sensor system is then considered. After studying the data obtained, a hazard detection algorithm is developed that accounts for all possible terrains given the sensor resolution. Computer simulation of the rover on various terrains is then used to test the entire hazard detection system.

I. INTRODUCTION

The use of remote sensors to explore the solar system has contributed much knowledge in the search for answers to numerous questions concerning, particularly, the origin of the universe and the existence of extraterrestrial life. Considerable effort has been focused on exploration of the planet Mars and successes achieved to date represent a great achievement. As with any good scientific investigation, however, more new questions have been raised than resolved. To answer these new questions, an extensive surface exploration of Mars should be undertaken. Regardless of the type of experiments to be performed, a thorough investigation of the planet surface should involve visiting many sites on a trajectory of several hundred kilometers.

One method of conducting widely separated experiments is to construct many sets of scientific equipment and to land one set at each site. While this plan is feasible, it requires much duplication of effort and hardware. Another alternative is a mobile science station that can visit every site. The time required to visit every site is now an important consideration. A vehicle that cannot deal with a wide variety of adverse terrains will have few traversable trajectories available. A higher mobility vehicle, on the other hand, can take advantage of more direct yet possible adverse terrains thereby minimizing travel time and maximizing science time. One suggested vehicle is a "tumbleweed" that is blown across the planet surface by wind. It is not likely, though, that the tumbleweed will reach all of the desired sites by chance. Furthermore, even such a high mobility vehicle can get permanently lodged in one location. For these reasons, the vehicle to be used should be controllable.

Selection of a desired path for a roving vehicle should proceed on several levels. Obtaining an overall view the ·ain to be traversed is a good first step. Without such information, the situation is similar to going on vacation without a road map. An unnecessarily long route will probably be taken. To gather information over several hundred kilometers, an orbiting sensor is a good choice. Due to a resolution of only 100-200 meters, however, many smaller objects that may be hazardous to the rover are not detected. Therefore, shorter range, higher resolution sensors are required in addition to the orbiting sensor. Compared to the long range sensor, short range sensors will have a higher scanning frequency and will require a higher frequency of path selection decision. Given long round trip communications delay times of from nine to forty minutes and limited "windows" during which information can be transmitted, direct earth control of the vehicle is not a routine matter. Most of the path selection decisions should originate on Mars. A manned mission to Mars is a possible solution but .s made difficult by the long duration of the mission, higher risk involved, additional payload required, and a necessary return trip. An autonomous roving vehicle with onboard short range sensors can provide a simpler alternative.

One possible strategy is to first plan a rough path to be traversed that avoids major terrain features based on orbiter sensor data. Television cameras on board the vehicle enable controllers on earth to locate landmarks and to choose intermediate targets along the route. Finally, a short range sensor with appropriate software is employed to teer the vehicle safetly from one target to the next.

The focus of this paper is to investigate the short range sensor concept. A general sensor scheme is proposed and its characteristics are analyzed. For a particular given sensor, a terrain modelling algorithm is developed and is tested and evaluated by means of computer simulation.

II. BACKGROUND

There are several shorter range sensor systems currently being studied. Techniques such as TV imaging and laser range finding are being developed for use over a range of about fifty meters. With these systems the vehicle stops, a scan is taken, the data are processed, a path is selected, and the vehicle moves along the desired trajectory. The only problem is that to get sufficient resolution over a fifty meter range, a large quantity of data and, therefore,much data processing time are required. The result is a vehicle moving only on the order of 400 meters per day. With a mission covering a distance several orders of magnitude greater, time becomes an important issue.

A better solution might be to maintain the same resolution while shortening the range to a few meters and, thus, decreasing the amount of data to be processed. With the increased scan and decision rates made possible by this short range system, vehicle speed can be greatly increased. The only drawback is a very limited field of view. The midrange sensors with a fifty meter range have a high probability of choosing as direct a path as possible over the fifty meter view. A short range sensor that can see only a few meters at a time will not necessarily choose the optimal trajectory. The short range system will prove to be superior if the effect of increased speed exceeds the effect of longer trajectories so that the overall vehicle displacement over time is increased. The increase in vehicle speed using a short range system is estimated to be at least one order of magnitude by virtue of the enormous data reduction. The midrange sensors are not expected to give a comparable reduction in path length. Even though a short range sensor is not likely to choose the optimal trajectory for a trip of several hundred kilometers, a fifty meter mid range scanner will probably not do much better.

Use of a short range sensor does not automatically rule out techniques such as TV or laser range finding. TV pictures do present a time problem, though, due to the extensive image enhancement techniques that must be applied. Decision rates on the order of one per second are necessary for a short range system to be feasible. While laser range finding data can be processed quickly enough, the technique is more difficult to implement over short ranges because of the increased difficulty in measuring time of flight.

An easier technique for obtaining accurate measurements with a laser over short ranges is triangulation. The system consists of a laser located on a mast with a laser detector located at a known separation, Figure 1. When the laser is pulsed, a short segment of the beam intersects the detector field of view. Knowing the pointing angles and locations of both the laser and detector, the location of the line segment of intersection can be determined by trigonometry. If a laser pulse strikes terrain lying within the detector field of view, scattered light is sensed. The terrain is then known to lie somewhere along the line segment of intersection. If no return signal is received, the terrain is assumed to lie elsewhere. By proper choice of pointing angles and detector size, a system can be developed in which a return indicates the presence of safe terrain while no return means a hazardous path. Rotating the mast enables the scanning of several azimuths in search of safe paths, Figure 2. Such a one laser, one detector system scanning fifteen azimuths at ten degree spacings has been tested at R.P.I.[1,2] The vehicle operated subject to assumptions that only terrains involving gradients of less than

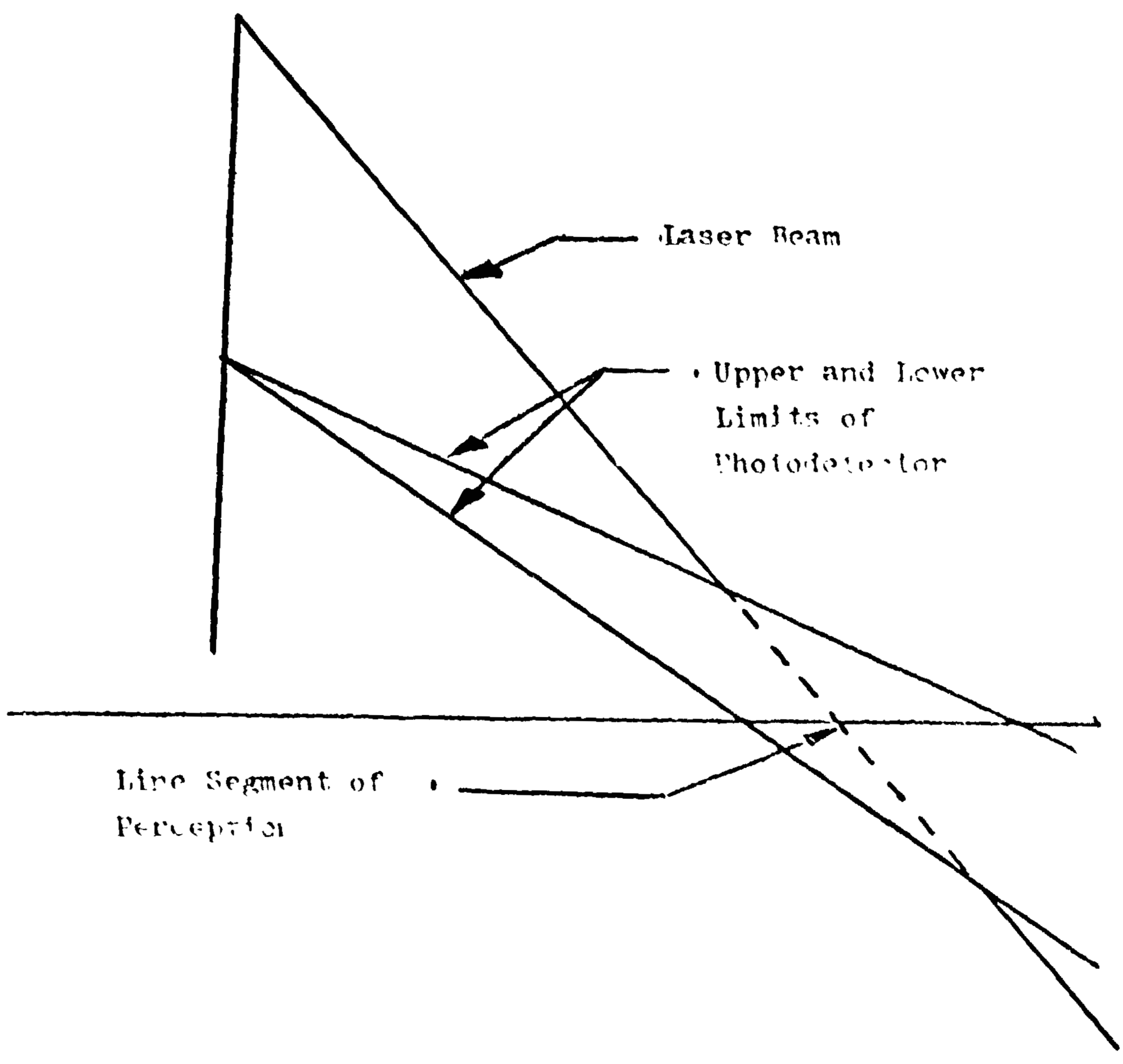

Figure 1. Laser-Detector Triangulation Scheme

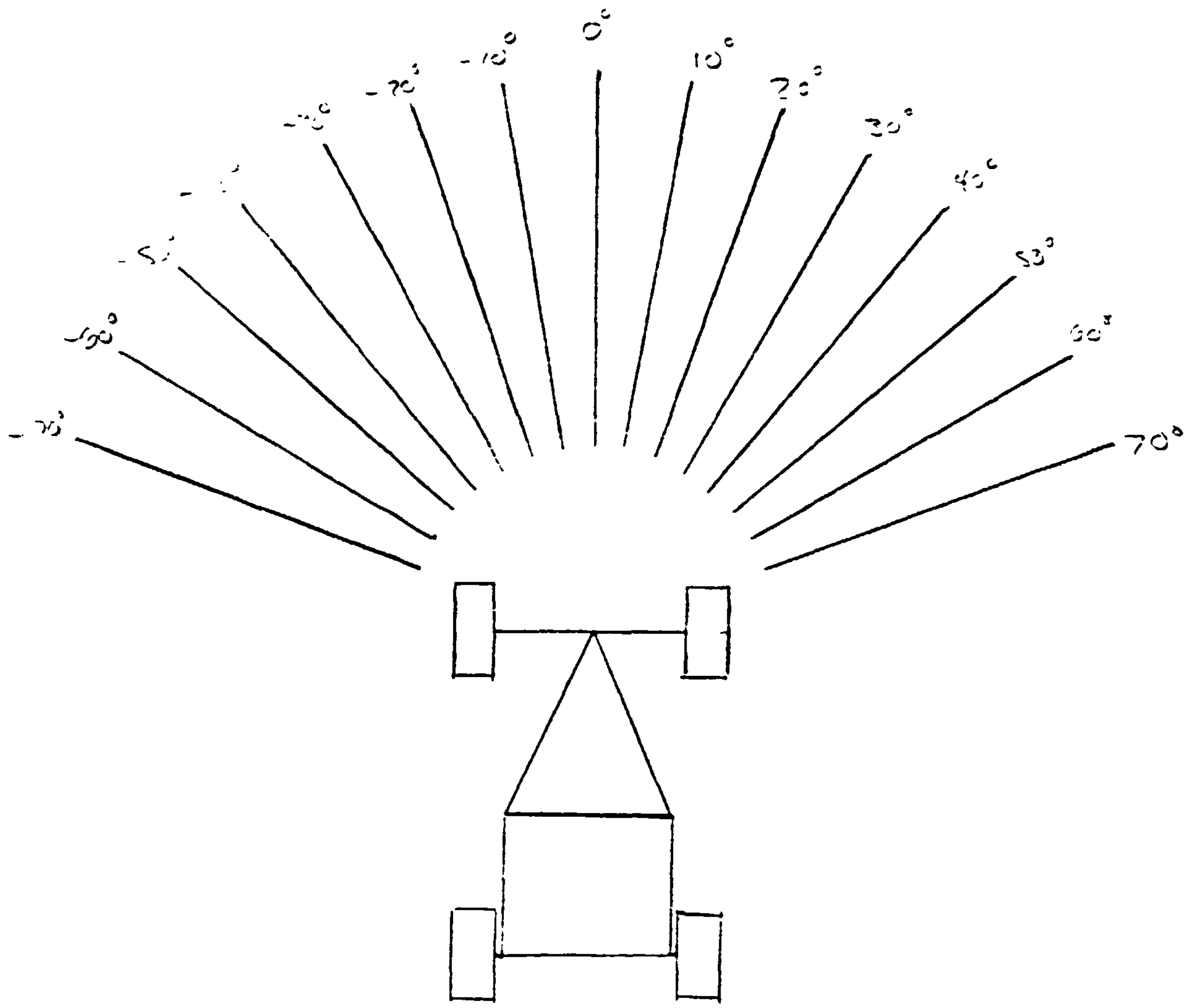

FIGURE 2

Top view of triangulation sensor showing sensed azimuths thirteen degrees and step obstacles with less than twelve inches differential were safe. All other terrains resulted in no return signal and were assumed hazardous. The surprisingly good performance obtained represents a remarkable achievement since this is the only hazard detection system to be successfully field tested.

While past investigations have demonstrated that the laser/ detector triangulation system can work, it is not clear that other systems will not perform as well. More sophisticated systems have a better chance of choosing more direct trajectories. If the paths chosen by the single laser/detector system are too erratic, the higher vehicle speed may not be enough to offset the effect of longer trajectories. The path selection problems are due to uncertainty. Any terrain is characterized by truly safe paths and unsafe paths, Figure 3. The job of the hazard detector is to choose the most direct path from the safe paths available. As with any real system, there is always some uncertainty added. The one laser, one detector system bases its decisions on very little information and as a result, many terrain classifications are unsure. With the success or failure of the mission dependent on avoiding dangerous situations, all unsure terrain must be classified as unsafe. The result is a smaller number of safe paths available and a reduced ability to select a more direct path. A more accurate system is characterized by less uncertainty and more available paths. Clearly, if the laser/detector short range triangulation hazard detector is to be competitive, the amount of uncertainty associated with each scan should be reduced.

The main source of uncertainty in the single laser/detector system is the low quality and accuracy of data. Additional laser firings and shorter

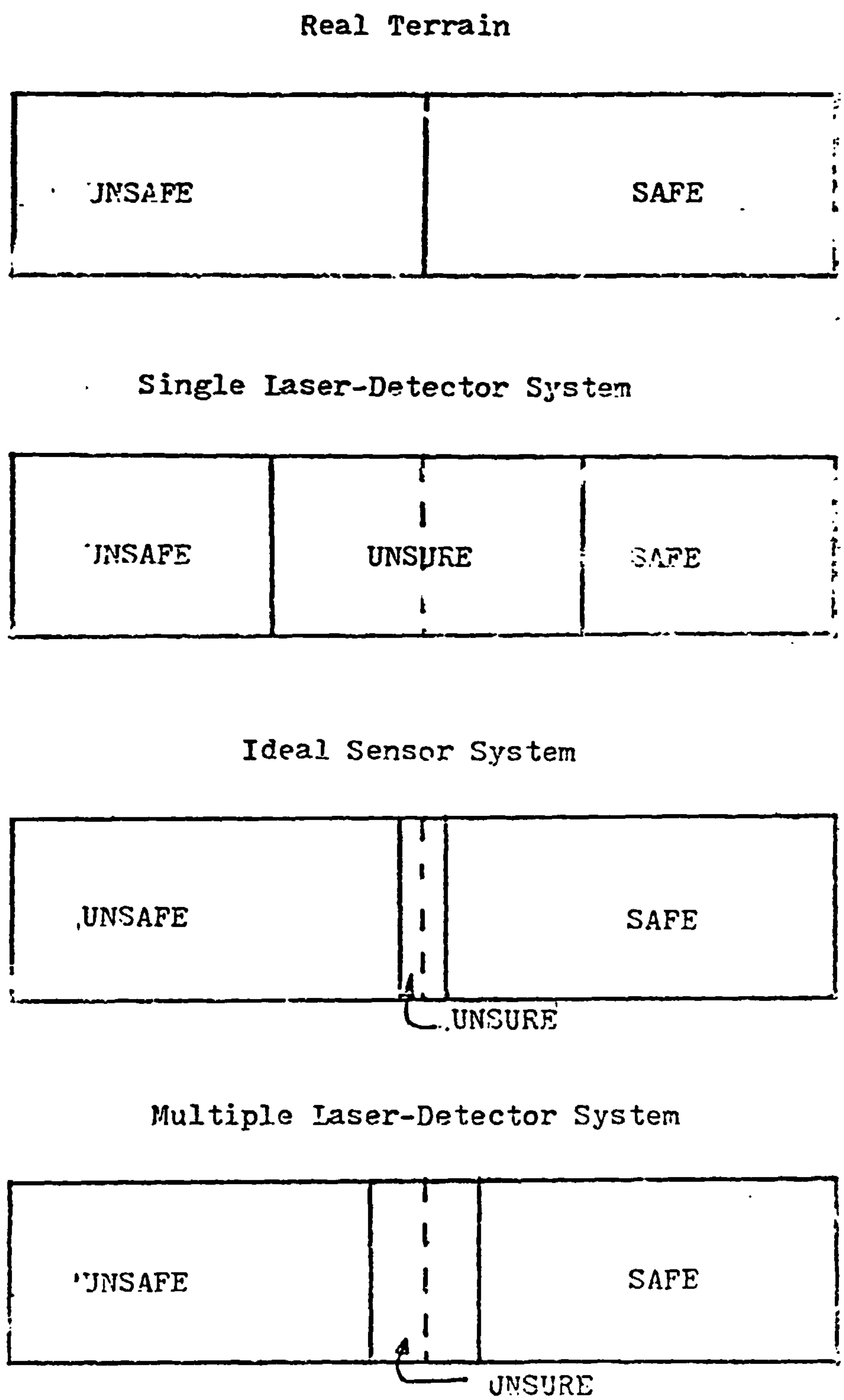

FIGURE 3
Terrain Classification

line segments of intersection would give a better terrain picture. A multi-laser, multi-detector system provides the extra data desired, Figure 4. Other sources of uncertainty, such as instrumentation error, are neglected because their effect on the lengths and positions of the line segments is assumed small. The multi-laser/detector hazard detection system is the short range sensor proposed for an autonomous Martian rover.

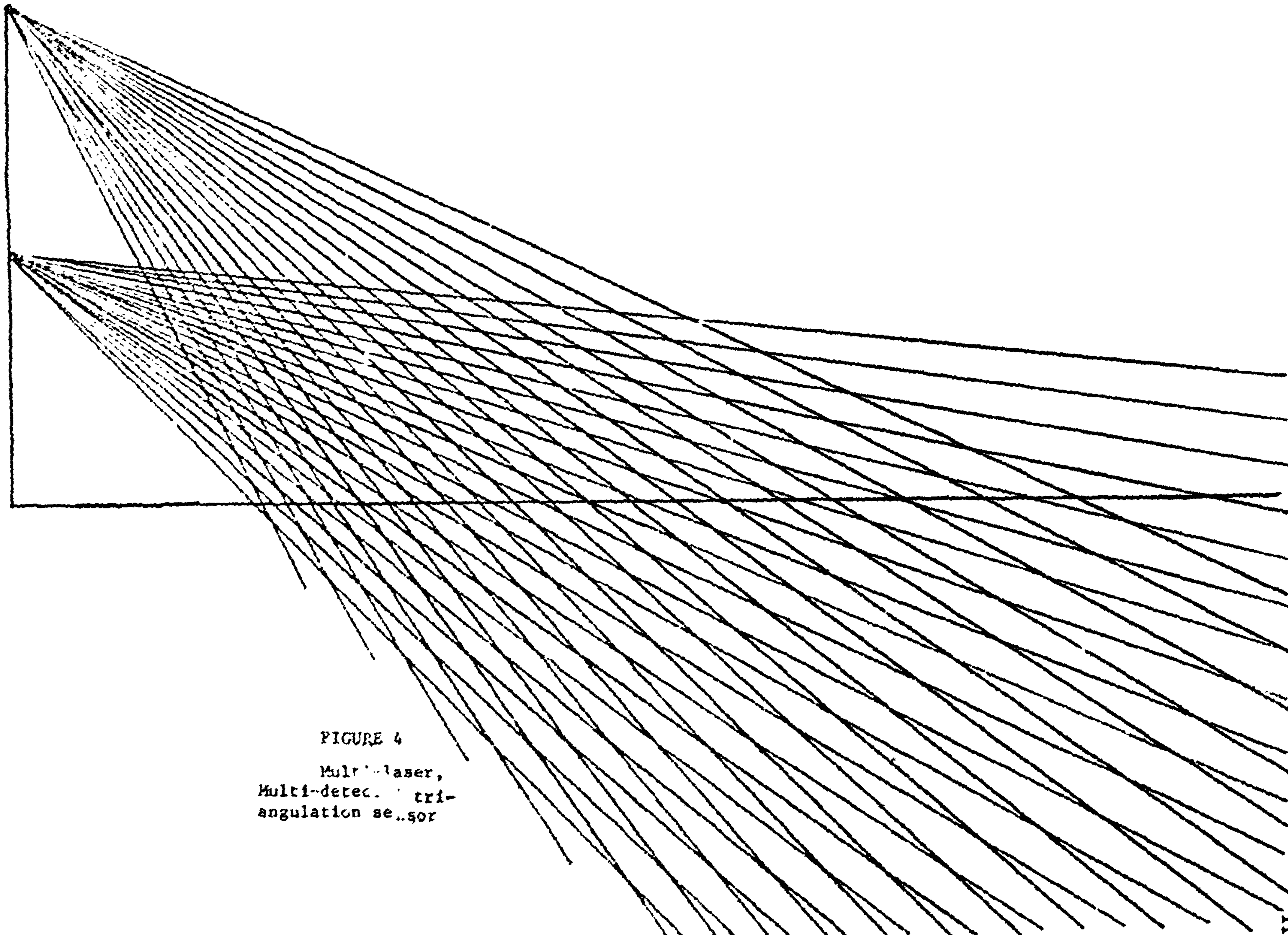

FIGURE 4

Mulr'-laser,
Multi-detec. ' tri-
angulation se..sor

III. THEORY

Figure 5 illustrates the generalized multi-laser, multi-detector system with a boulder in the field of view. The data obtained are shown as the darkened line segments. Note that while it is obvious from the data that a bump occurs in the terrain, the actual contour is not clear and a wide variety of terrain features is possible, Figure 6. In general, a single scan does not necessarily produce data that define unambiguously a particular obstacle. It is helpful to learn what the perception capabilities of the system are and which parameters can improve perception.

Probably the greatest limitation on the perception results from the discreteness of system. In order to perceive desired features or terrain fluctuations, there is a minimum data spacing or rate of sampling that must be observed. There is a direct analogy to sampling of electronic signals. In theory, a signal that has a finite bandwidth can be uniquely reconstructed after sampling if the sample rate is at least twice the highest frequency contained in the signal. What this means for terrain sensing is that if high frequency or highly fluctuating terrain is ignored, the original terrain can be uniquely reconstructed from sensor data by choosing the sampling rate sufficiently high. To some degree the assumption that rapidly fluctuating terrain does not exist is a valid one since features such as spikes, poles, or tree trunks are not likely to be found on Mars.

Unfortunately, the theory discussed above assumes that the signal is well known at the sample points. This is not necessarily true for the triangulation sensor. The sample points are really line segments. Even if high frequency terrain perturbations are ignored and if the proper sampling rate is observed, the original terrain cannot be uniquely reconstructed from the data, Figure 7. The most that can be hoped for is to define an envelope

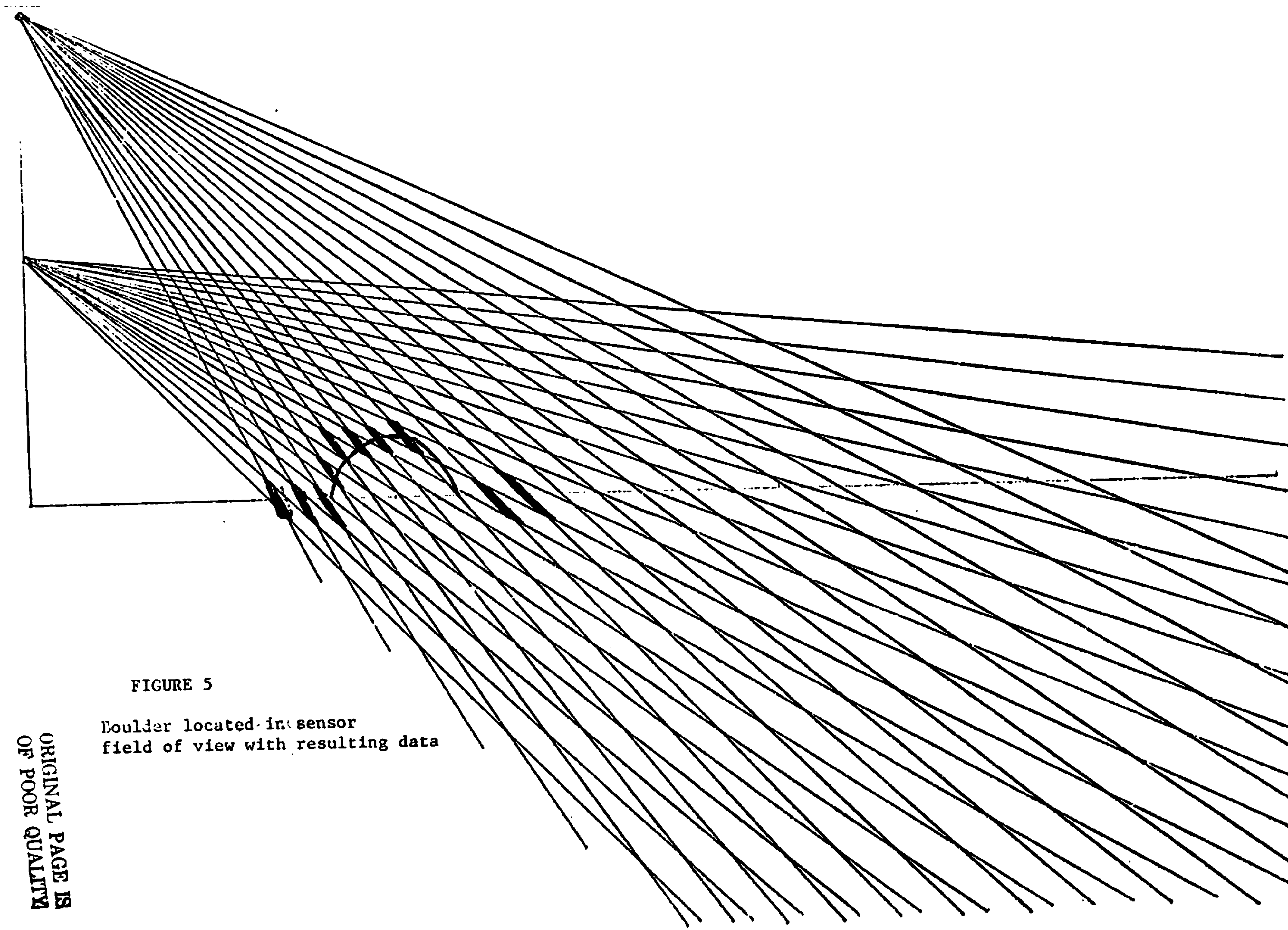

FIGURE 5

Boulder located in sensor field of view with resulting data

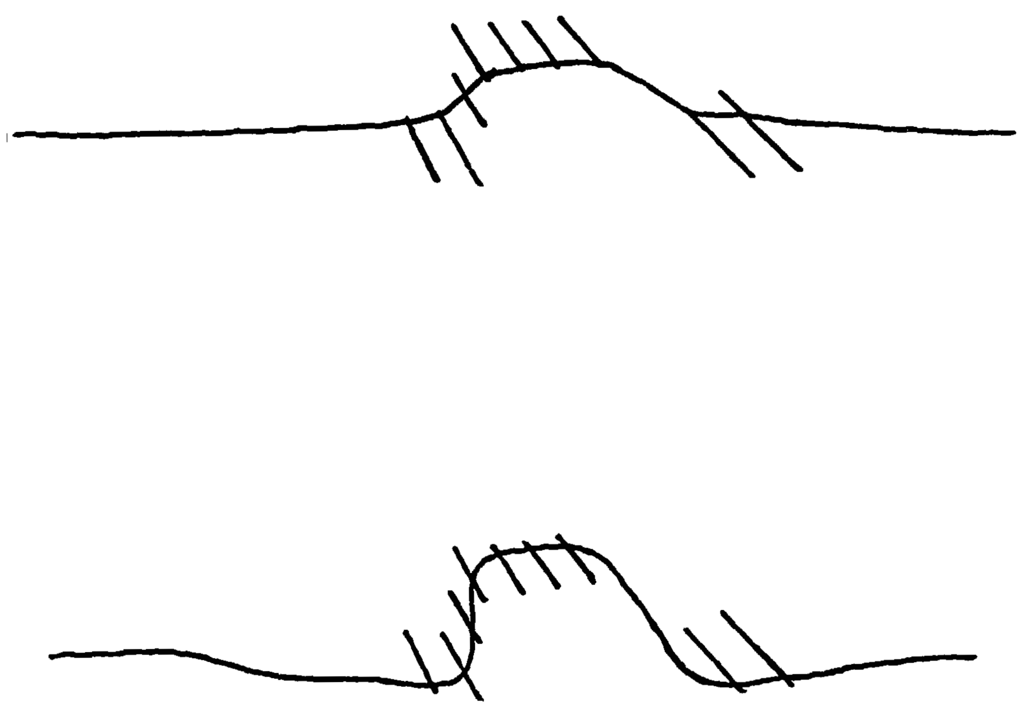

FIGURE 6

Example of ambiguity associated with sensor data

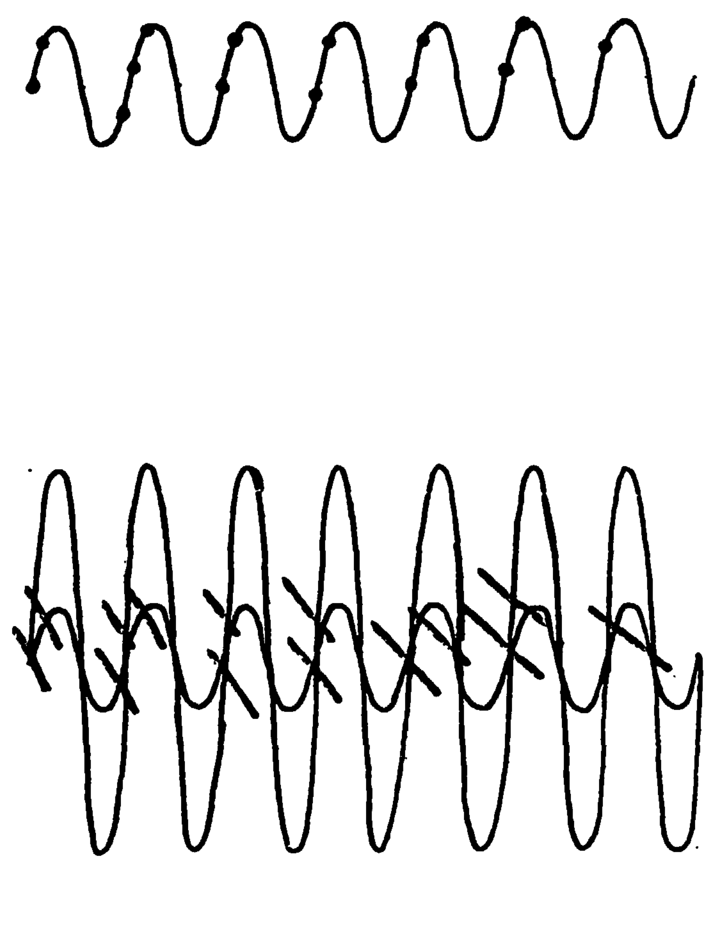

FIGURE 7

Example of ambiguity resulting from uncertainty at sample points in which the terrain lies. While it is not trivial in practice, in theory it is possible to determine the entire range of terrains possible given a set of data assuming that high frequencies are ignored. The size of the envelope can be reduced by observing that extreme terrain fluctuations are not possible between data points since other adjacent detector would have sensed the terrain. Therefore, given the sensor data and some a priori knowledge of the character of Martian terrain, an envelope can, in theory, be constructed in which the terrain is known to lie. While this is not as good as completely specifying the terrain location, at least the possible terrains are bounded and the uncertainty in terrain location is reduced.

One of the keys to better perception is to reduce the size of the terrain envelope. A logical conclusion may be that more laser pulses at intermediate elevation angles will make the envelope better defined. Doubling the number of laser pulses does improve the situation and additional lasers reveal an interesting problem. Since adjacent laser shots are usually seen by the same detector, the pattern of line segments is very structured, Figure 8. As the number of laser pulses approaches infinity, the data actually become a series of contiguous quadrilaterals resembling parallelograms, Figure 9. What is of interest is that the parallelograms are well defined. Each parallelogram is joined to its neighbors only at opposite vertices. The four sides are formed by the edges of an individual detector field of view and two laser pulses. If the locations of all common vertices are known from the pointing angles of the corresponding lasers and detectors, then the parallelograms are uniquely defined. The conclusion is that all of the information obtained from an arbitrarily large number of laser shots is totally represented by the location of the n+1 vertices where n is the

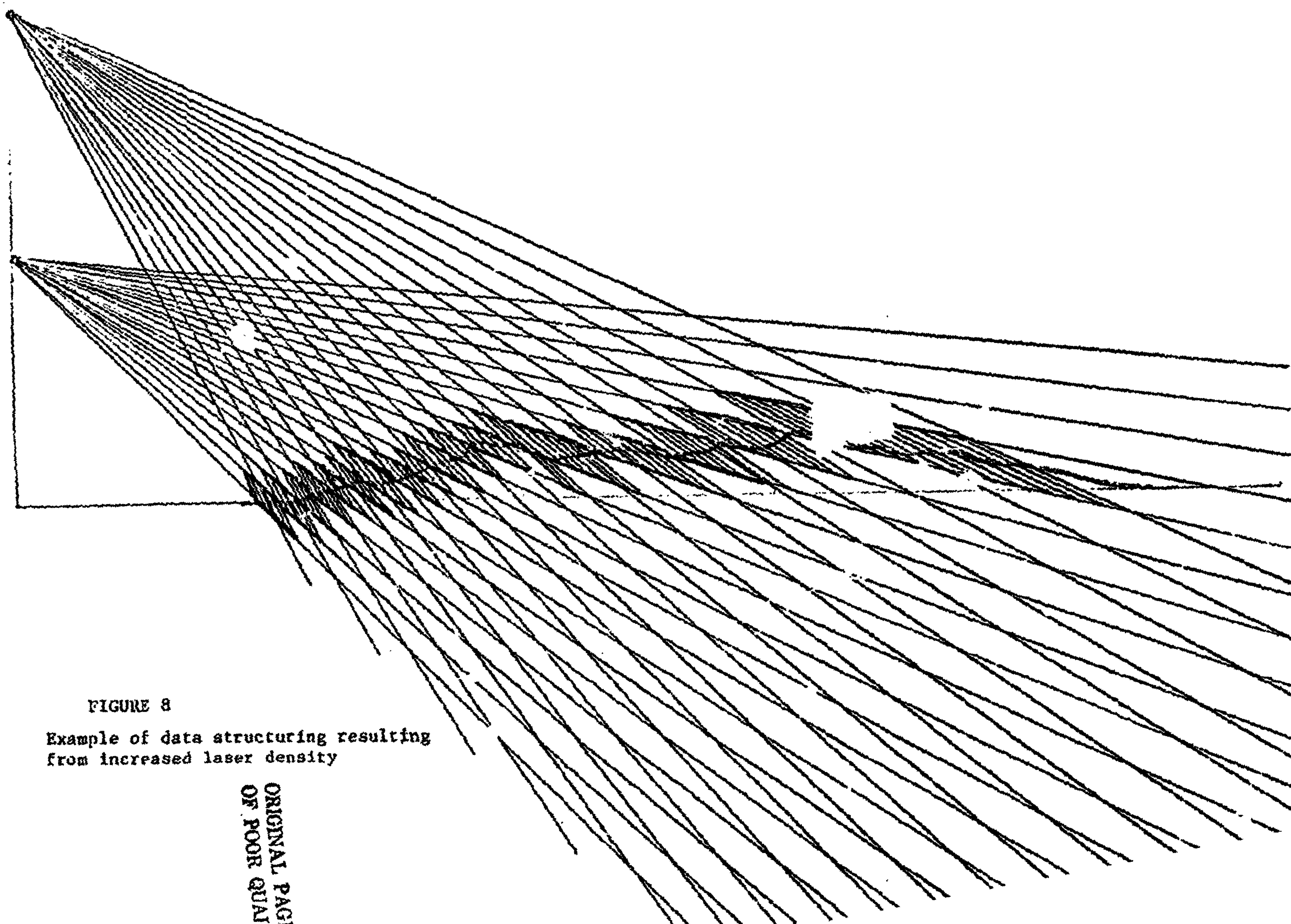

FIGURE 8

Example of data structuring resulting from increased laser density

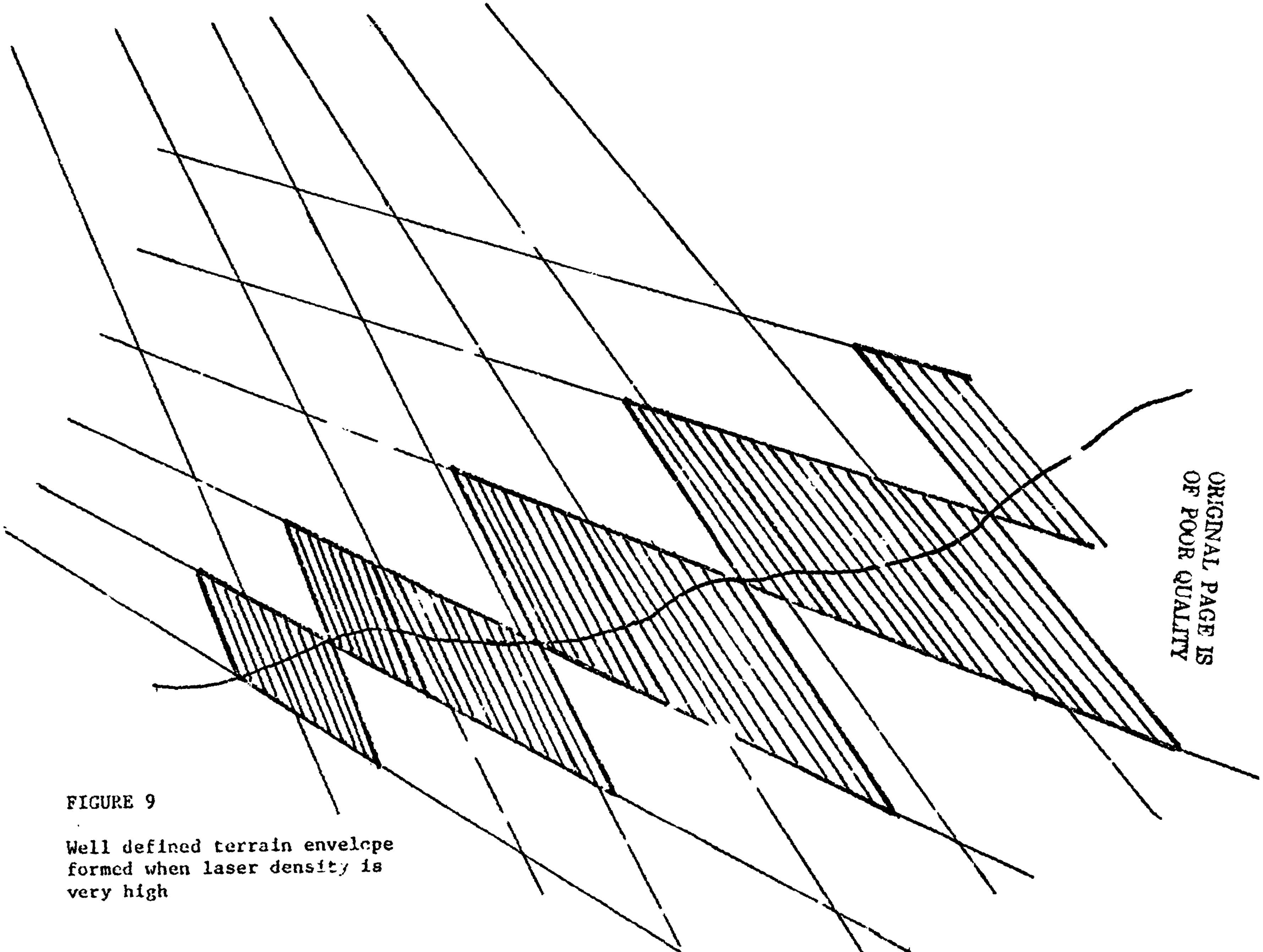

FIGURE 9

Well defined terrain envelope formed when laser density is very high number of detectors. Since all vertices occur at detector boundaries, the laser need only be fired at those points where the terrain intersects detector boundaries. Knowing the laser and detector pointing angles, the envelope can be constructed. A continuous laser that scans for this occurrence will do the job.

The above findings provide an easy method for obtaining an accurate terrain envelope. Furthermore, it can be concluded that each additional laser contributes a decreasing marginal increase to the amount of information. There is an upper limit to the amount of information and, hence, a laser limit to the uncertainty associated with a given number of detectors and an arbitrary number of lasers. The amount of information available from a finite detector system can be maximized without increasing the amount of data that must be processed.

Just as decreasing the laser spacing gave improved perception, similar benefits should be obtained by decreasing individual detector sizes. Smaller detector fields of view shorten the line segments of intersection and decrease the uncertainty associated with each measurement. Wherever data are taken, the location of the terrain is known more accurately. The effect is to decrease the size of the terrain envelope. In the limit as the detector fields become infinitessimally narrow, the line segments of interaction are reduced to points, Figure 10. This is the case of ideal sampling where the terrain is uniquely reconstructed from the data when the proper sample rate is observed.

From the above analysis it is now known that laser density determines the sampling rate and, thus, the number of data points while the detector den[illegible]es the data accuracy. It is possible, although not alw[illegible]fine an envelope that bounds the set of possible terrains

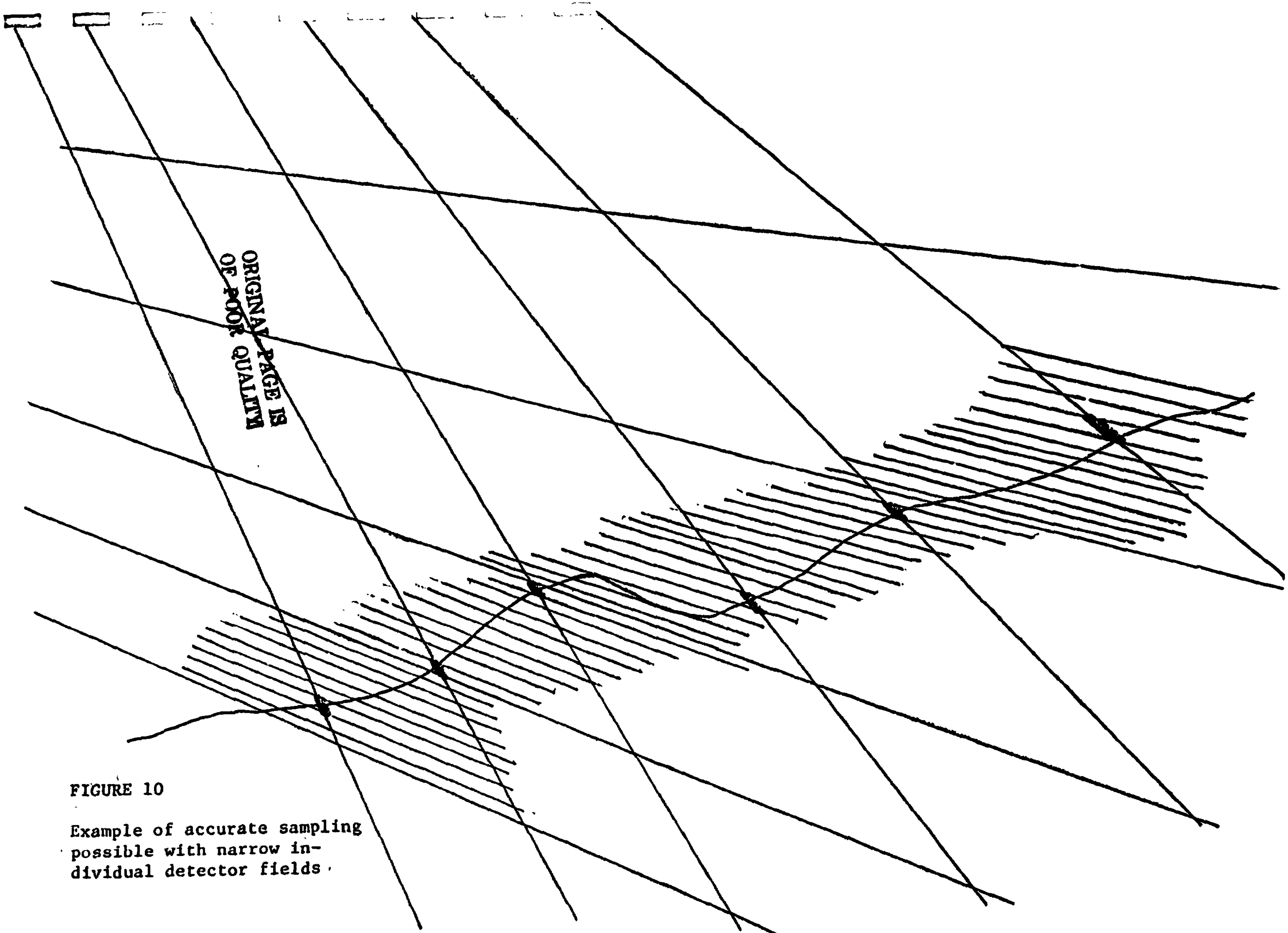

FIGURE 10

Example of accurate sampling possible with narrow individual detector fields given a set of data. It has been shown that an accurate envelope can easily be generated by using a continuous laser that scans the terrain for detector boundaries. Furthermore, this system represents the optimum usage of the laser since the maximum amount of information is extracted with a minimum of data. The use of very narrow individual detector fields with a sufficient number of laser firings yields data from which the actual terrain can be uniquely reconstructed.

While the conclusions drawn look promising, there are practical considerations that cannot be overlooked. The main thrust of the analysis has been to account for all of the possible terrains that may have given rise to a set of data since, for safety's sake, even the improbable terrains cannot be overlooked. A terrain envelope performs this function and, in theory, one can always be generated. Except for a few special cases, though, no method has been developed for generating these terrain bounds in the general case. Even in the two special cases of narrow laser spacing and narrow detector fields, the validity of the expected terrain envelope breaks down. In these cases the measurements being made are so fine that the assumption that measurement error can be neglected no longer holds. The message here is merely a reminder that what can be done in theory is not always true in practice.

There are other considerations to be made when specifying a sensor system. The overall detector field of view is of critical importance. One reason for a short range sensor is to maintain high resolution with a small number of individual detectors. Yet, there is a lower limit to the size of the field. The field of view must be wide enough to see sufficiently large sections of obstacles so that meaningful decisions can be made. Another constraint is that, particularly under large vehicle pitch conditions, rapidly rising or falling terrain may fall outside of the sensor field of view, Figure 11.

The location of the lasers and detectors is also a factor. With the laser and detector clusters restricted to being on the same mast, better results are obtained with a larger separation between the laser and detector clusters. Increasing their separation increases the angles between laser beams and detector fields and decreases the lengths of the line segments of intersection, Figure 12. There are practical limits to the degree of separation. The laser height cannot exceed the mast height while the detectors must be high enough to clear the ground.

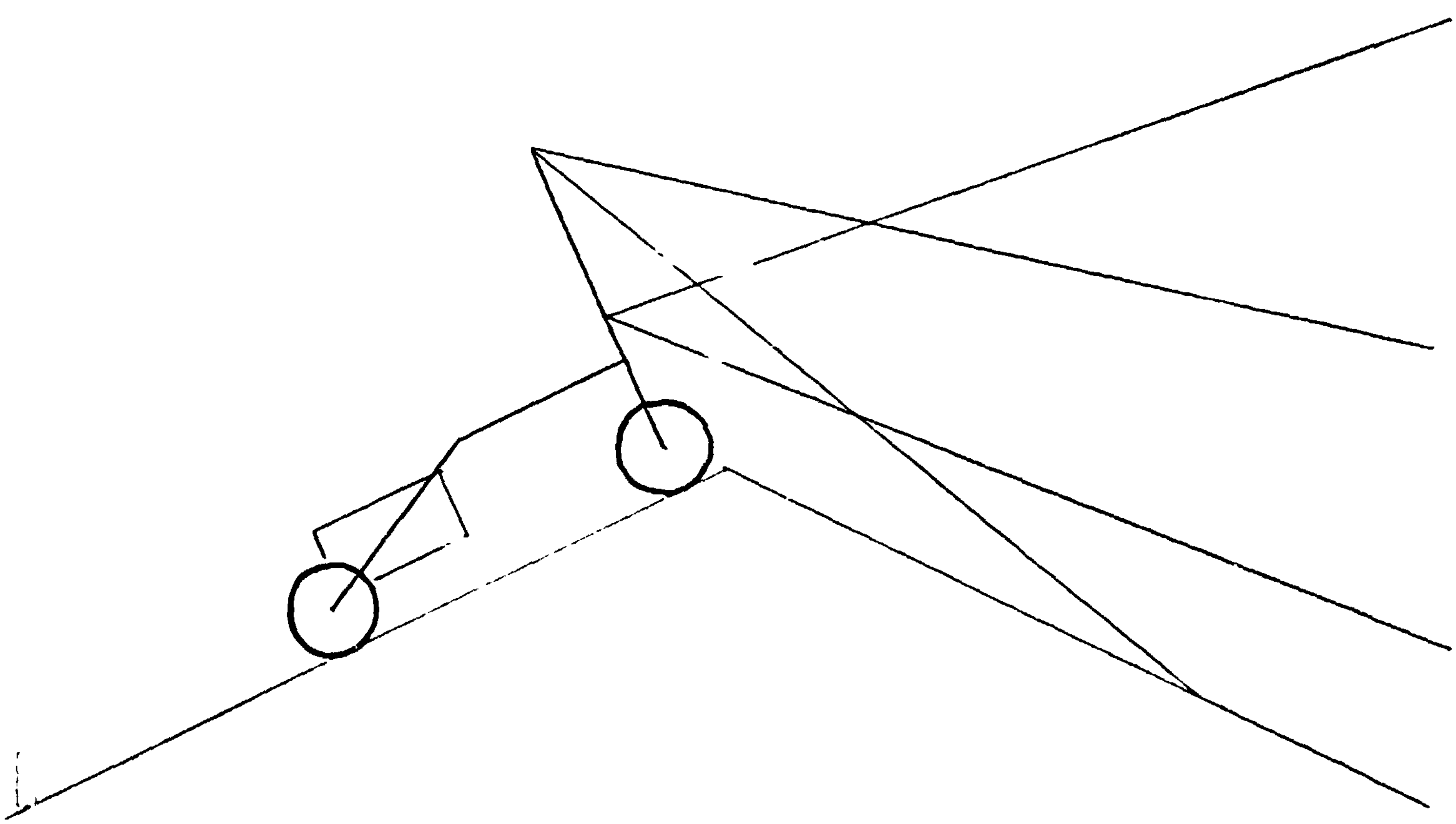

FIGURE 11

Small sensor field loses sight of terrain

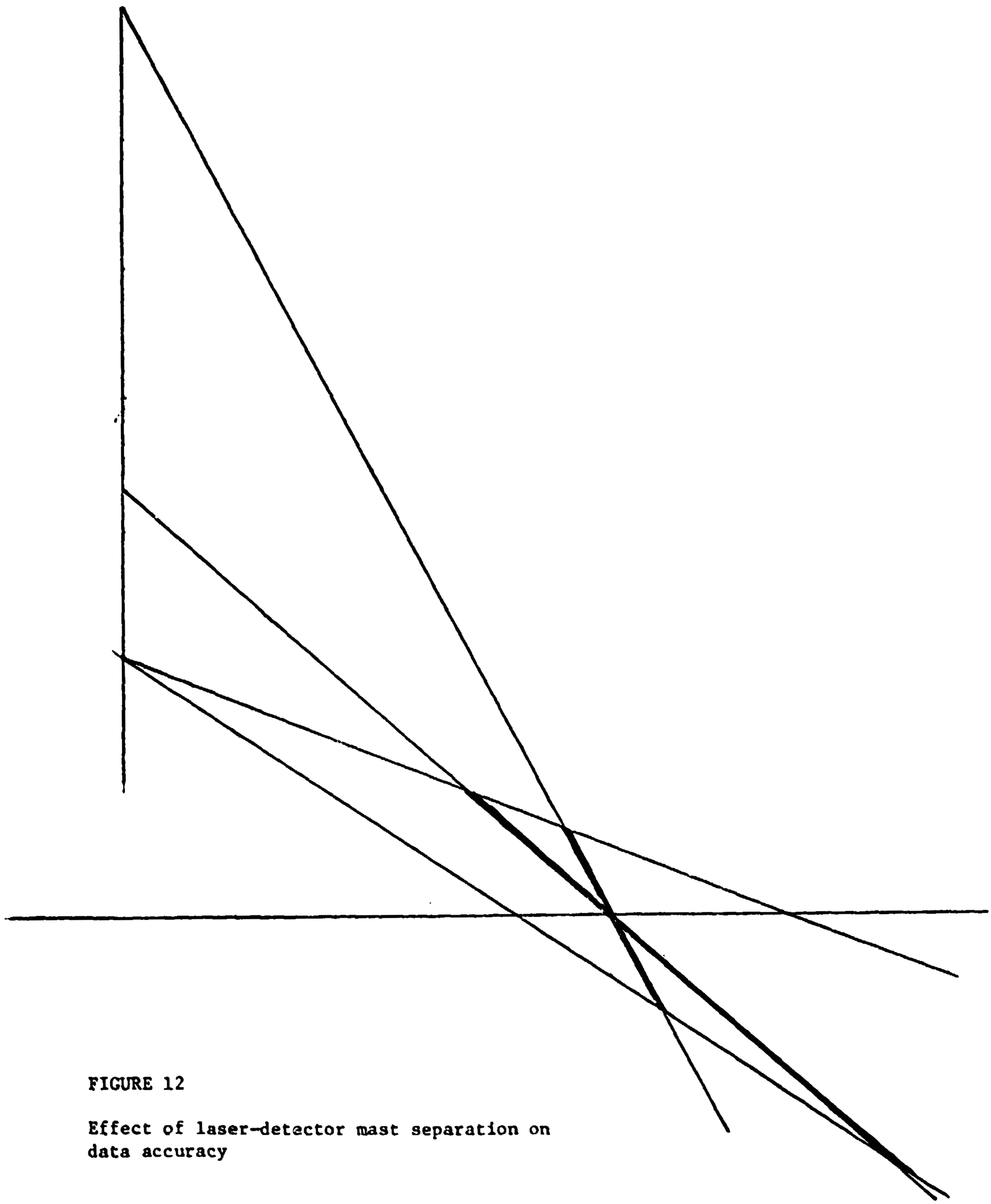

FIGURE 12

Effect of laser-detector mast separation on data accuracy

IV. THE ELEVATION SCANNING LASER/MULTI-DETECTOR CONCEPT

Having gained some knowledge about general multi-laser, multi-detector sensors, attention is now focused on the specific case of the elevation scanner laser system under development at Rensselaer. The geometry is identical to the general case but there are some very important parameter constraints. For simulation purposes, the lasers are placed at the top of the mast at a height of 2.0 meters and the detectors are located at a height of 1.0 meter, locations which compare well to actual vehicle dimensions. The lowest laser and lowest detector are aimed to intersect level ground at 1.0 meter. This distance is chosen because obstacles closer than 1.0 meter cannot be safely avoided without a backup maneuver. The laser firings can be variably spaced but must have an average separation of at least one degree. Only twenty detectors with equal fields of view are available and this represents a major problem. A tradeoff must be made between resolution and overall field of view. The vehicle encounters terrains varying in slope from -30° to 30° and will need a 60° field of view to deal with the most extreme situations. Using proper optics the 60° field can be obtained but the individual detector fields must be 3° each. The resolution possible from such a system is not sufficient to detect certain obstacles. More will be said on this issue later. As a compromise, 2° detector fields with a 40° overall field of view are chosen for simulation. To maintain a "square" array where laser and detector densities are equal, there will also be 20 laser firings of 2° increments. A base design has now been developed with which experiments can be undertaken, Figure 13.

The remaining task is to develop an algorithm for interpreting

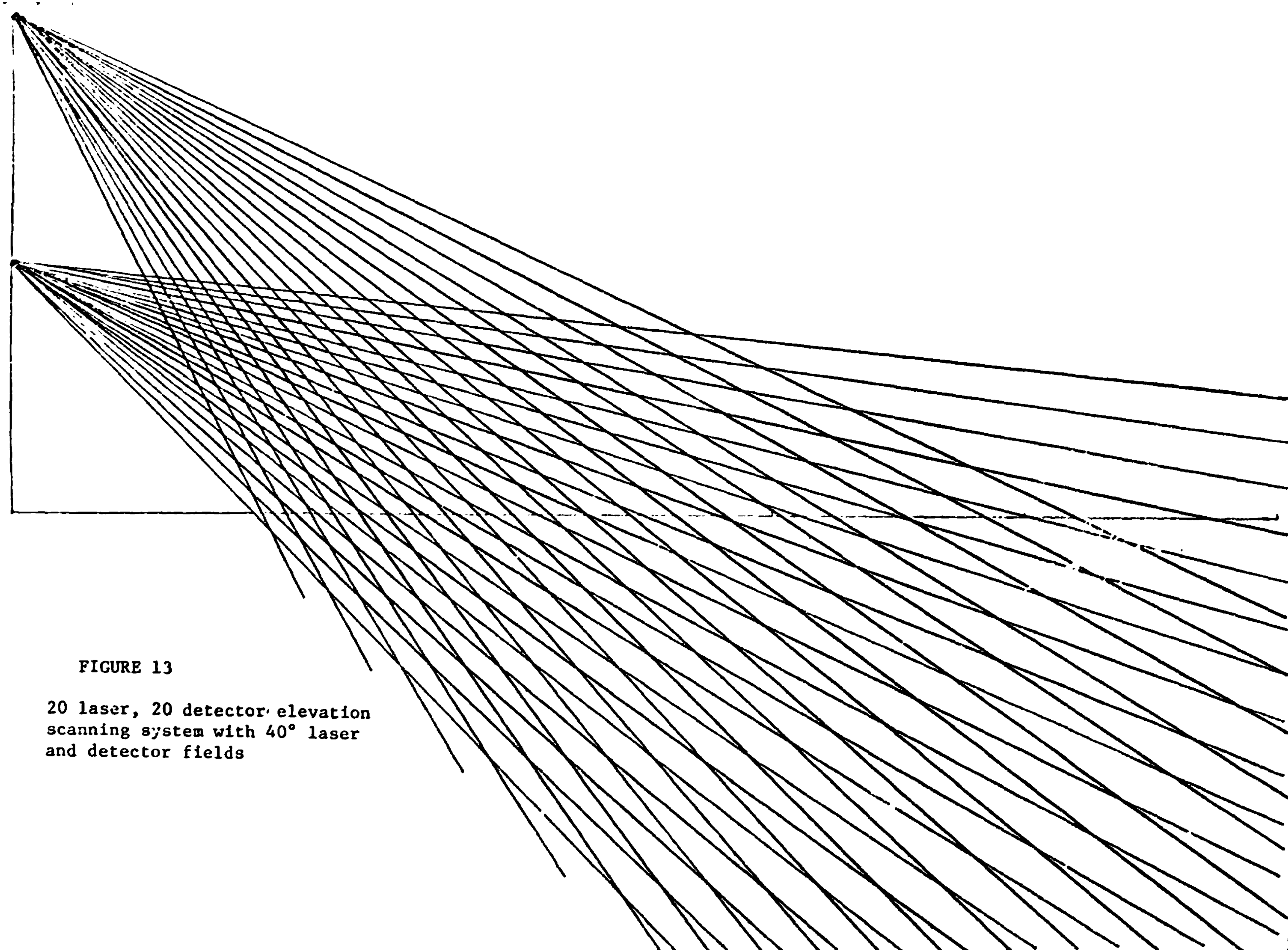

FIGURE 13

20 laser, 20 detector elevation scanning system with 40° laser and detector fields

sensor data that, given the uncertainty inherent in the system, accounts for all possible terrain features. Unfortunately, none of the earlier findings can be applied in this case. The 2° individual detector fields result in such large line segments of intersection that ideal sampling and unique reconstruction of the terrain is not possible. In many cases, the lengths of the line segments equal or exceed the dimensions of obstacles. A terrain envelope can be easily generated using a continuous laser but this is not possible given the hardware on the R.P.I. rover. A continuous laser cannot even be reasonably approximated by the particular pulsed laser being used. The reason is one of insufficient power dissipating capability. To achieve an acceptable signal to noise ratio of laser to ambient light each laser pulse must be of a certain minimum power. This power level is large enough compared to the laser's power rating that the maximum allowable pulse rate must be kept low. Clearly, another method must be developed for bounding the terrain. Furthermore, the method must be kept simple given the additional constraint of limited computer support available to the R.P.I. vehicle.

V. DATA PROCESSOR FOR HAZARD DETECTION

A method for processing laser data is suggested by analyzing the raw data. In the typical return matrix from a single azimuth scan, Figure 14, each column represents the result of the firing of a single laser. The position of the number "1" in a column indicates the detector that received a return after the laser pulse. The number "2" is used instead of "1" if the return fell on level ground in the context of a vehicle fixed coordinate system. The "3"'s are inserted as a reference line indicating the returns that would have been received if the terrain had been level. By taking the difference in position between the actual data and base terrain data, the measurements representing the terrain in a given azimuth can be reduced to a diagonalized return,[3] Figure 14. This set of data gives an indication of the level of the terrain above or below level ground. Application of the diagonalized return concept to the R.P.I. system defined earlier is somewhat misleading. Notice that the line segments of intersection fall into curved bands, Figure 15. The diagonalized return concept would be more useful if the data fell into straight, horizontal bands that corresponded directly to the diagonalized return levels. Such a system can be achieved by proper choice of laser and detector pointing angles. The particular detector system to be used, however, is constrained to uniform spacing. A good approximation to horizontal levels is possible with evenly spaced detectors by aiming laser pulses at the center of intersection of the individual detector fields with level ground. This modified arrangement which replaces the original system is defined as a quasi-linearized array, Figure 16. Notice that the uppermost laser pulses are of little use since they intersect the detector field at too great a

"LASER-SENSOR RETURNS"

3=REFERENCE TERRAIN

1=NORMAL RETURNS

2=RETURNS ON REFERENCE TERRAIN

LASERS

SENSOR	1	2	3	4	5	6	7	8	9	10	11
16	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	1
13	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	1	0
11	0	0	0	0	0	0	0	0	1	0	3
10	0	0	0	0	0	0	0	0	0	3	0
9	0	0	0	0	0	0	0	1	3	0	0
8	0	0	0	0	0	0	1	3	0	0	0
7	0	0	0	0	0	1	3	0	0	0	0
6	0	0	0	0	1	3	0	0	0	0	0
5	0	0	0	0	3	0	0	0	0	0	0
4	0	0	0	2	0	0	0	0	0	0	0
3	0	0	2	0	0	0	0	0	0	0	0
2	0	2	0	0	0	0	0	0	0	0	0
1	2	0	0	0	0	0	0	0	0	0	0

DIAGONALIZED RETURN

SCAN											
1	0	0	0	0	1	1	1	1	2	2	3

FIGURE 14

Typical sensor return matrix and corresponding diagonalized return

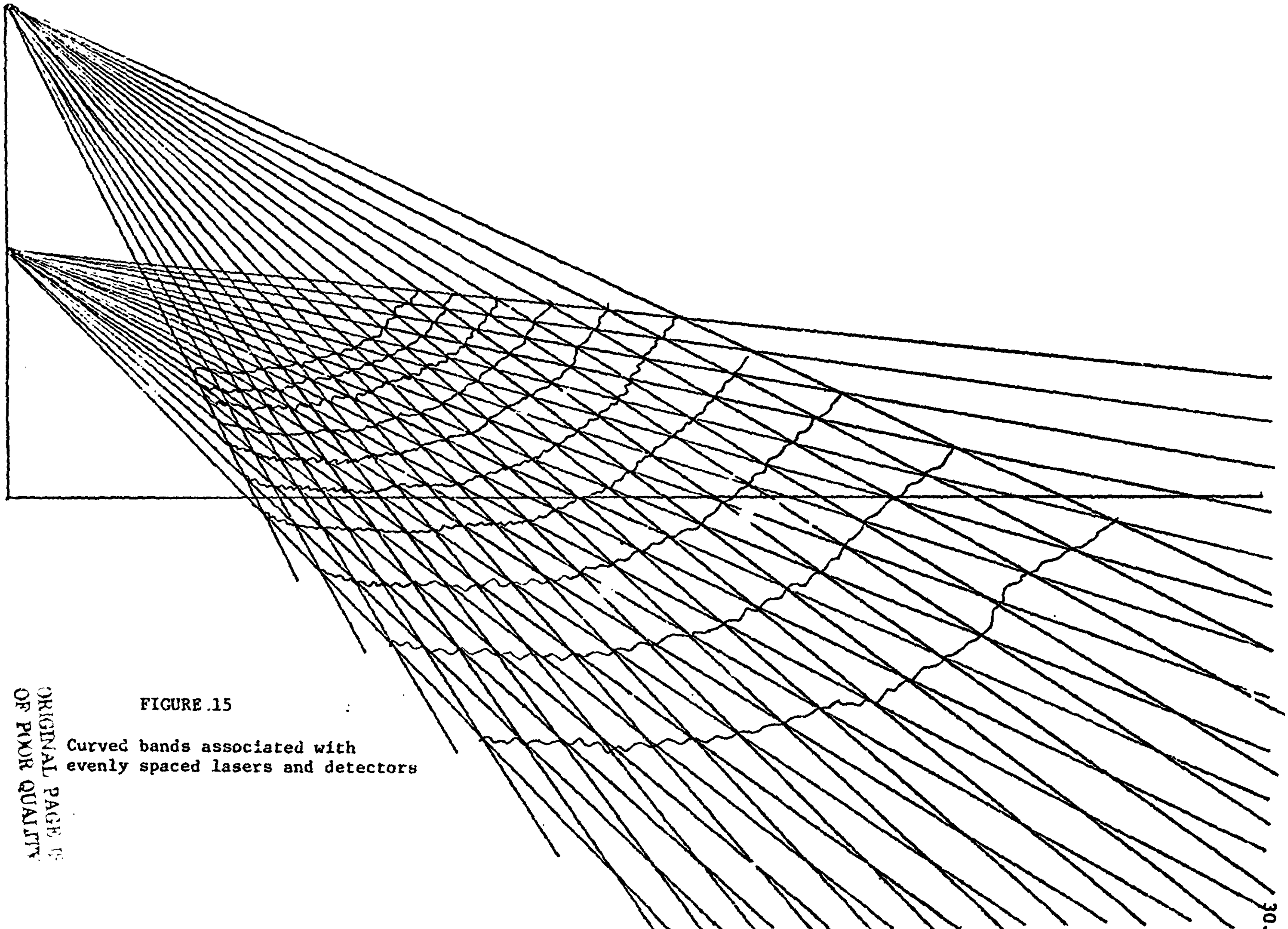

FIGURE 15

Curved bands associated with evenly spaced lasers and detectors

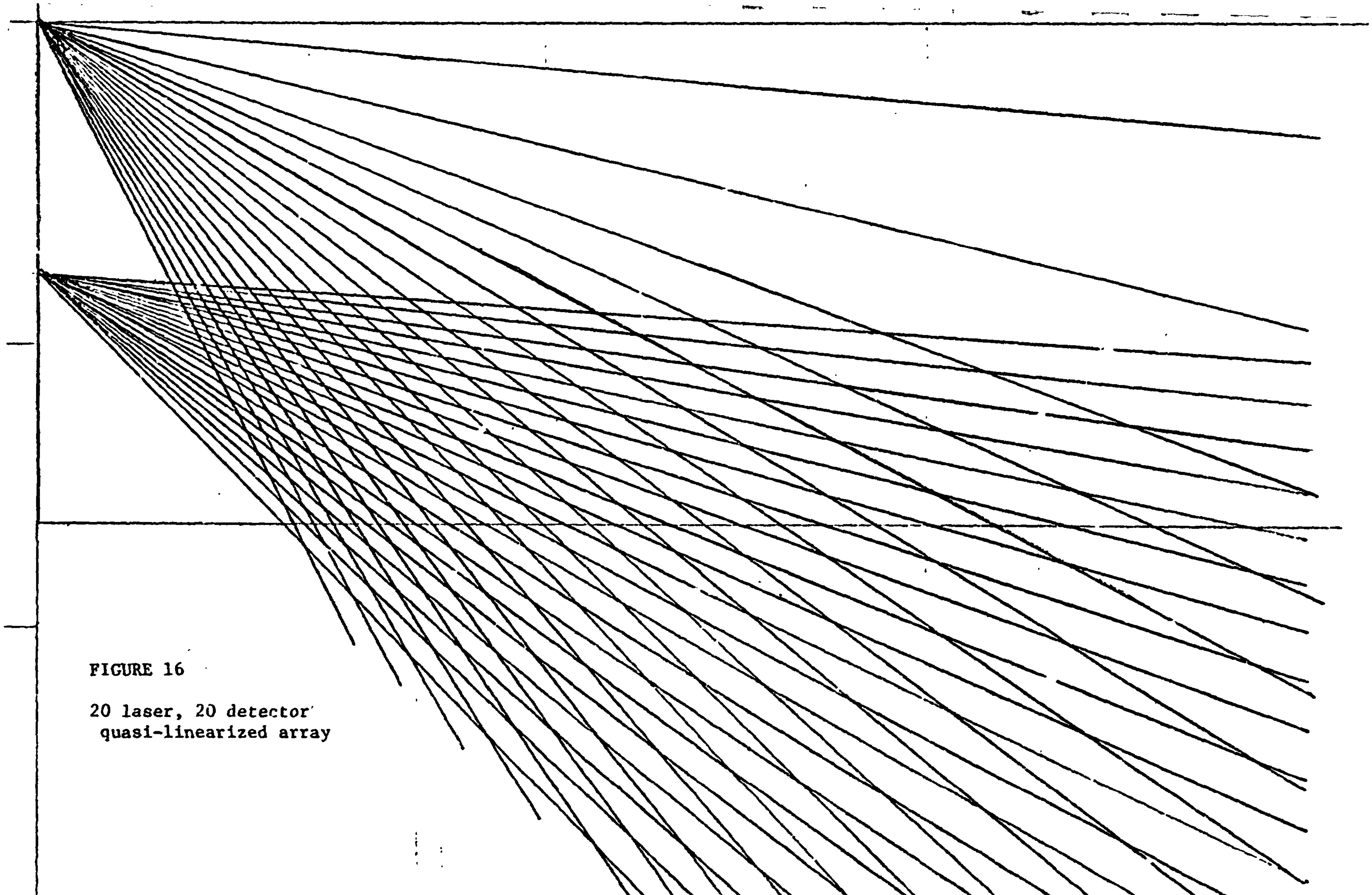

FIGURE 16

20 laser, 20 detector quasi-linearized array

range. For this reason, these higher elevation angles are omitted leaving 15 laser pulses and 20 detectors, Figure 17.

Scanning an arbitrary terrain with the quasi-linearized array reveals that the terrain data are actually quantized by the roughly horizontal discrimination levels, Figure 18. Regardless of the contour of the terrain, each set of data maps the terrain into a set of steps. Any one of the possible patterns can be completely and uniquely described by the location and magnitude of the steps.

Given the well defined patterns, a possible data interpreting scheme might be to associate a particular pattern with a particular terrain feature. There are some problems to be dealt with if this idea is attempted. First, there is not a one-to-one correspondence between terrains and patterns. With an infinite number of possible terrains but only a finite number of possible patterns, each pattern represents an infinite number of terrains. Even though the set of patterns is finite, there are very many of them. Attempting to match up a given data set with one of a large set of stored patterns can be a great bookkeeping and searching task. Finally, the quasi-linearized array is by no means uniform. The pattern associated with a particular terrain feature varies with the relative position of the feature within the array. In spite of these difficulties, pattern recognition may still be a viable solution and is left open to other investigations.

Before attempting to derive an algorithm to process sensor data for hazard detection, a clear and concise definition of a hazard must be developed. A generalized definition is desired for two reasons. First, the simpler the definition is, the simpler is the task of analyzing the data for hazards. Second, the definition cannot be so specific that it requires more information than is available from the data. To obtain some

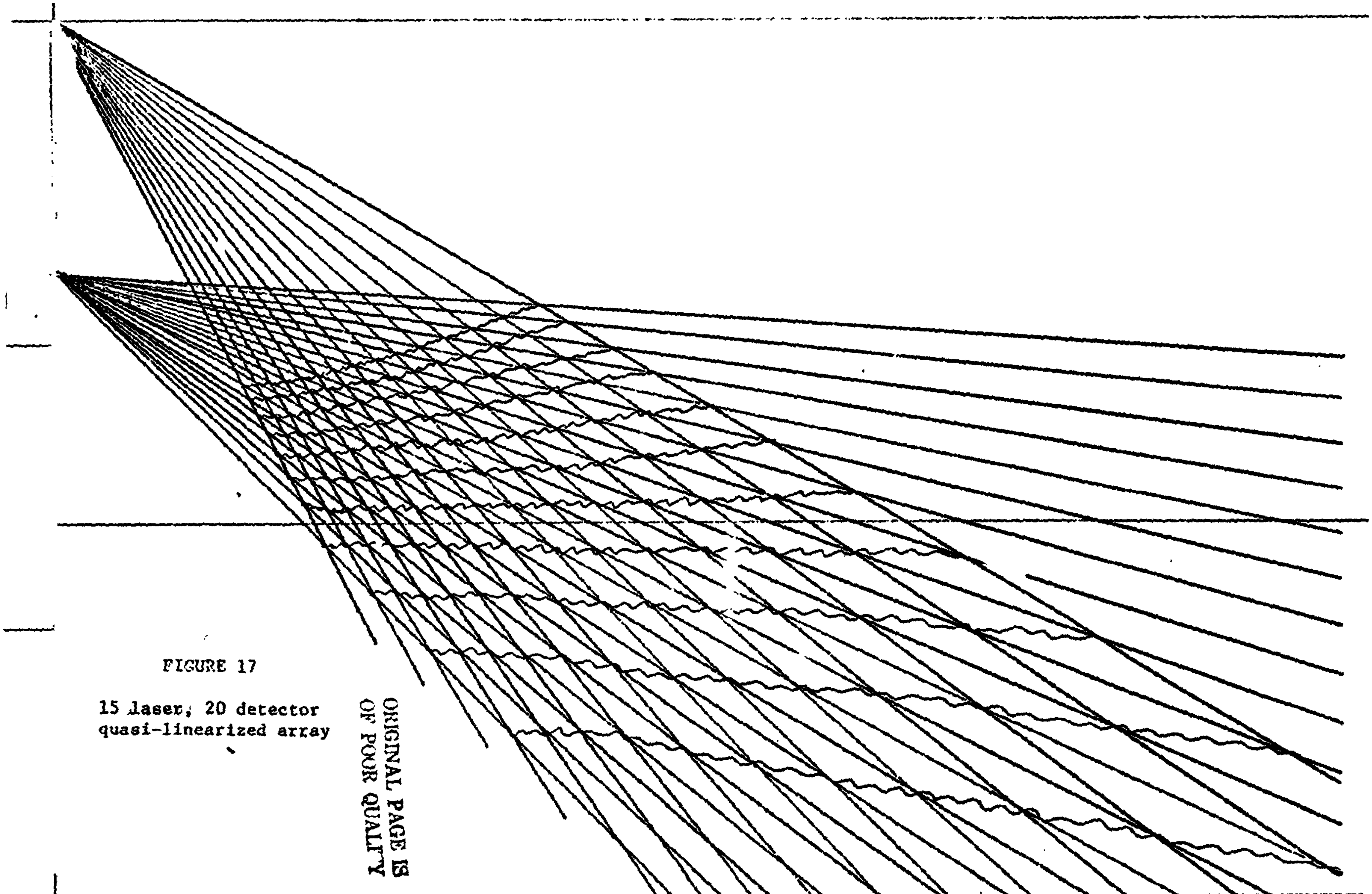

FIGURE 17

15 laser, 20 detector
quasi-linearized array

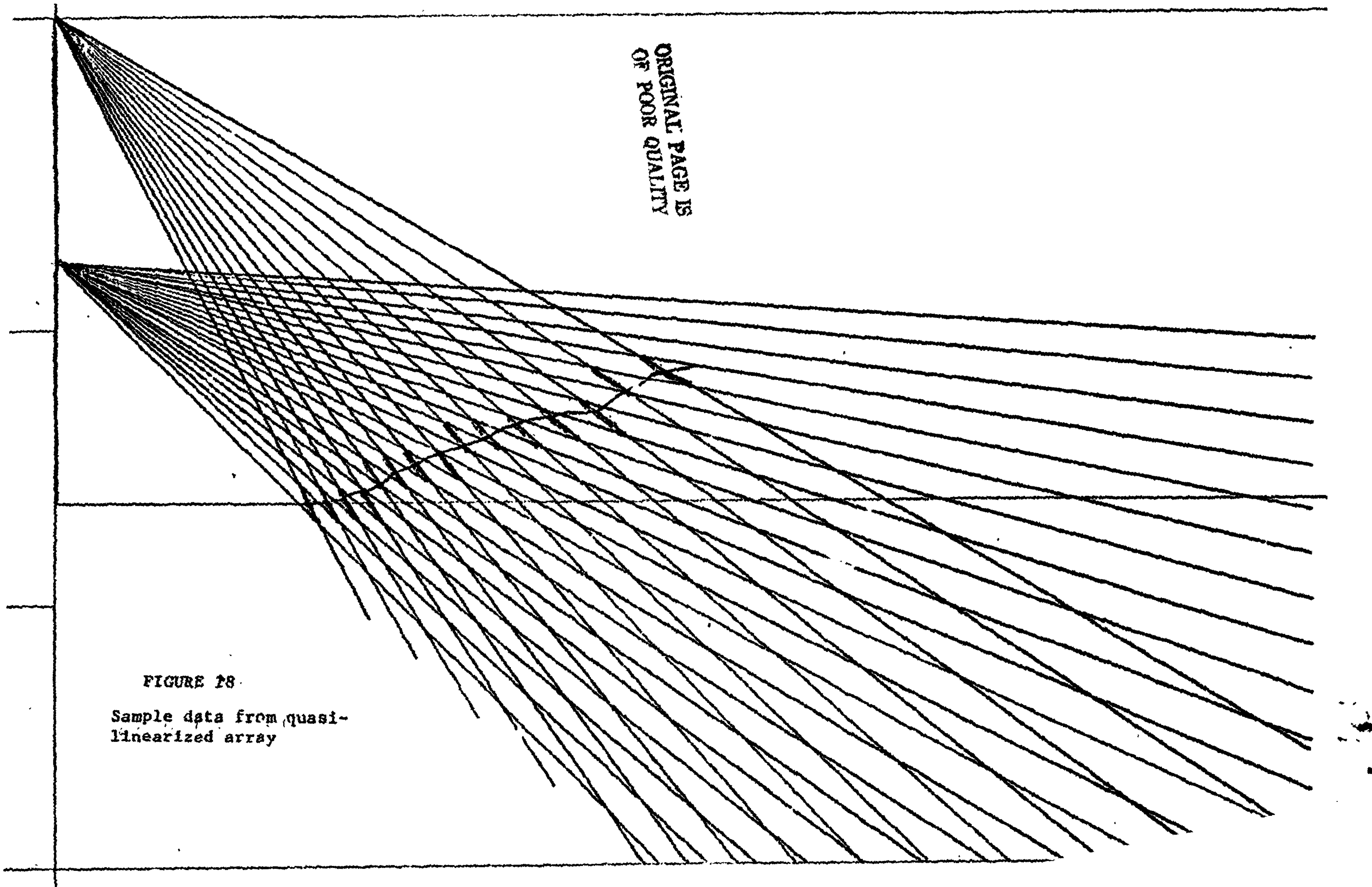

FIGURE 18

Sample data from quasi-linearized array

crit .a for identifying obstacles, the vehicle's mobility characteristics must be considered. From tests it is known that the vehicle can climb a maximum of a 30° slope and descend a -30° slope. The step climbing ability is limited to a height equal to the wheel radius of 0.25 meters. It is assumed that the same limit applies to negative steps. Restating the above more simply, any feature whose vertical height exceeds 0.25 meters and whose slope magnitude exceeds 30° is a hazard. These criteria have been established for a vehicle on level ground but do not necessarily hold if the vehicle is pitched. When the vehicle's inpath slope exceeds 20°, additional positive obstacles cannot be tolerated. An analogous rule applies to the negative case. The crude rules thus presented form an initial point for investigation. The criteria are simply defined and apply to all terrain features.

Having defined what an obstacle is, all that remains is to extract the desired information from the available data. The test for critical height can be easily done since the array is organized into essentially horizontal height levels. There are, of course, restrictions to be placed on the site of the quantization bands. If the levels are chosen to be so large that they exceed the critical step height, then significant terrain features cannot be detected. By choosing the levels to be sufficiently small, a critical altitude change is revealed as a step change in the data. Thus, a relatively simple way of testing for possible obstacles is to scan the diagonalized return for level changes.

There is, however, some ambiguity possible, Figure 19. While the figure shows two obstacles of different heights, the diagnolized return is

0 0 0 1 1 1 0 0 0 0 1 1 1 1

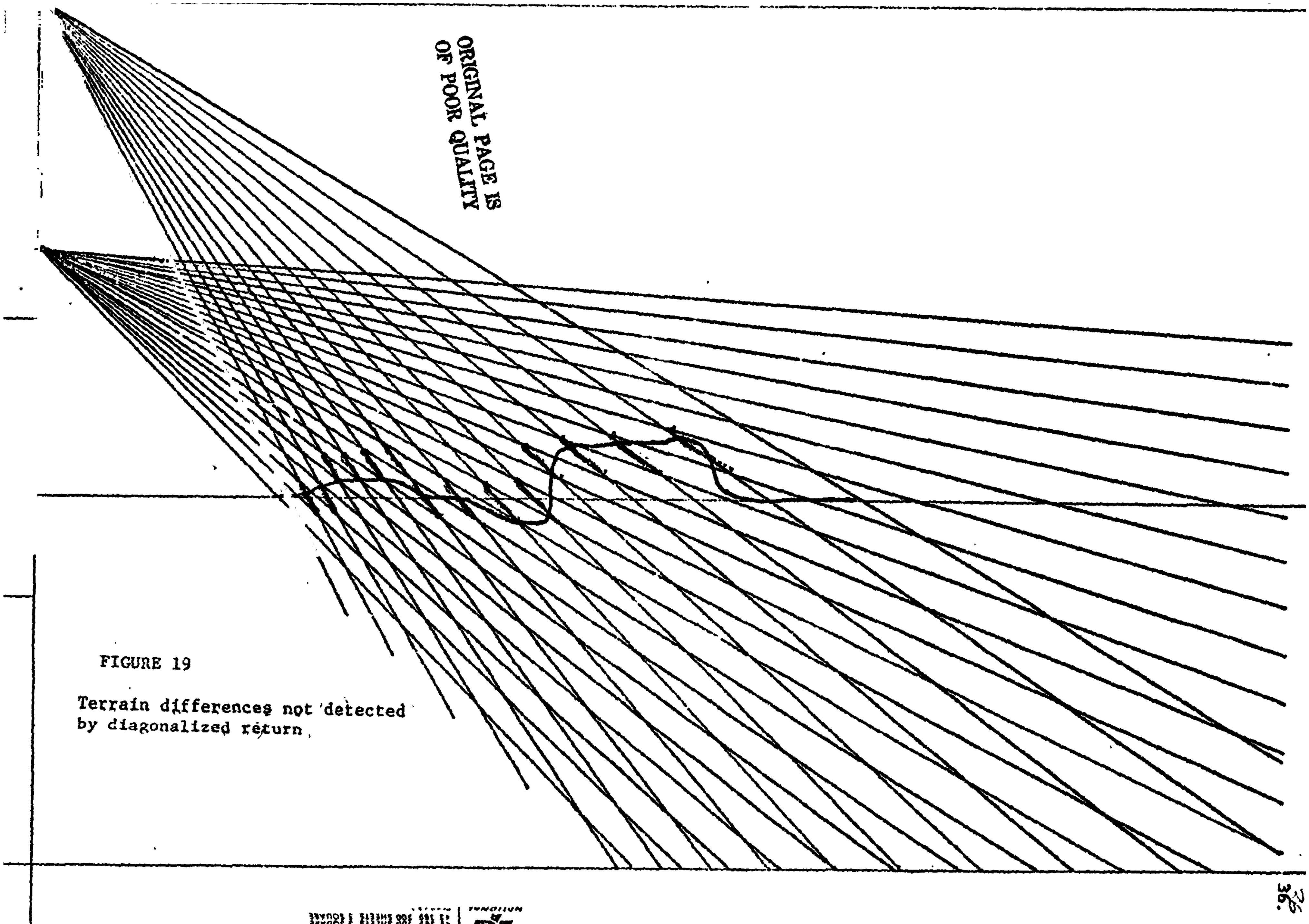

FIGURE 19

Terrain differences not detected by diagonalized return and indicates two objects of identical height. The coarseness of the quantization does not allow a better distinction. If the larger object is a hazard but the smaller object is not, then a serious problem exists. Any terrain perturbation, regardless of size, that crosses the boundary between two quantization and causes a level change in the diagonalized return is an unsure case and must be classified as unsafe. Since the probability of any arbitrary but safe terrain crossing a quantization level is quite high, almost all terrains would be viewed as hazardous. To remedy this situation the restriction must be imposed on the width of the quantization levels that a 0.25 meter terrain rise will result in at least two level changes in the data. Unfortunately, it is difficult to meet this condition with the twenty detector array. Due to the geometry of the array the lasers, detector fields, and discrimination levels diverge as the distance from the vehicle increases, Figure 20. To impose the condition that the width of two adjacent discrimination levels be no more than 0.25 meters even in the most distant areas of the array would require very narrow individual detector fields and thus, a prohibitively small overall field of view. The only alternative is to compromise by satisfying the condition only in the area near the vehicle, Figure 21. The restriction creates a very myopic vehicle that will accurately detect only large obstacles at large distances. Perception improves as the vehicle approaches until a range is reached where perception accuracy reaches desired levels. To insure that every terrain section is examined in the accurate area, the rover displacement between successive scans must be made sufficiently small.

The inherent discreteness of the array has so far been only a source of problems. Yet, there is one benefit derived from discrete data. The quantization of data "filters out" small terrain perturbations in much

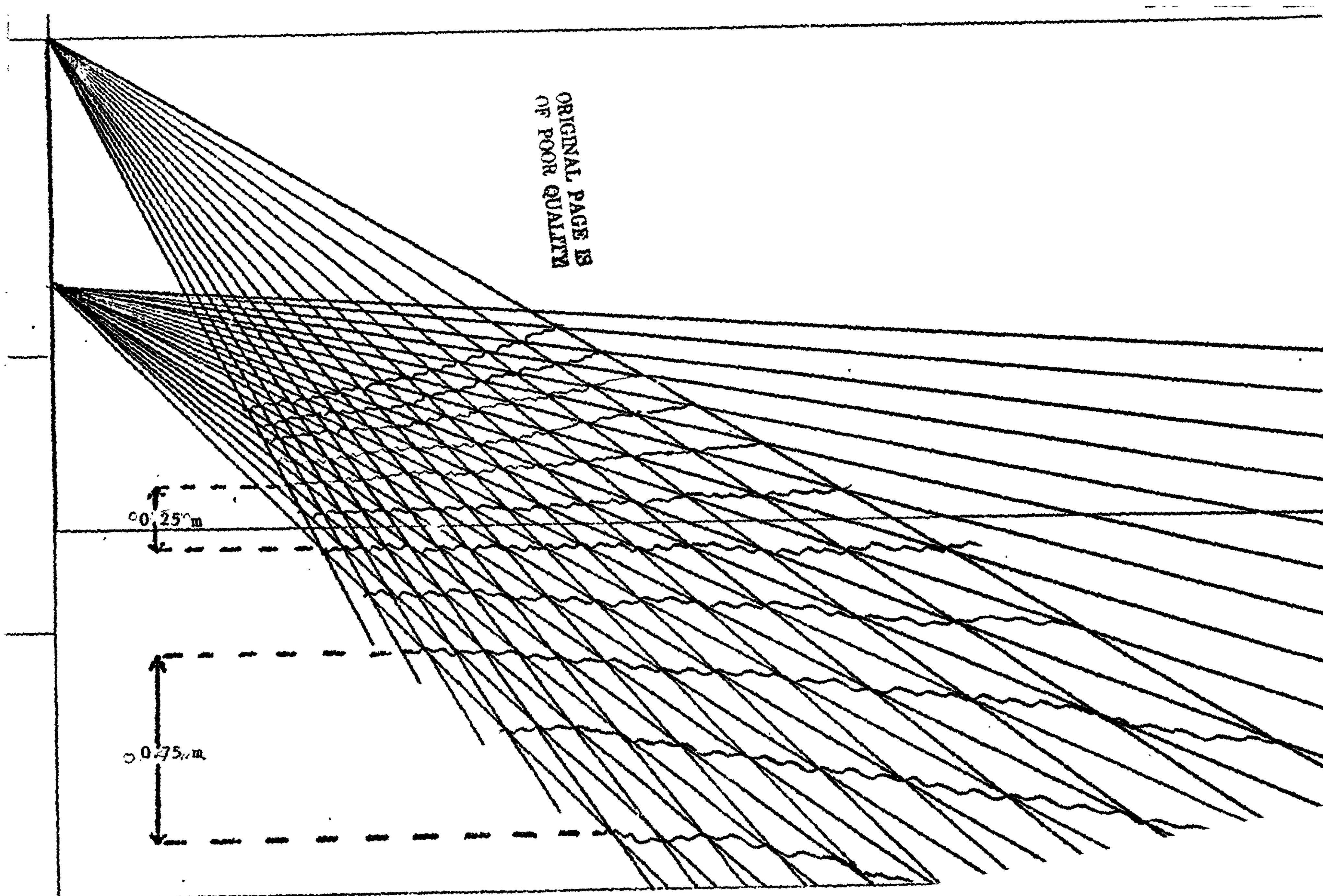

FIGURE 20. D[illegible]

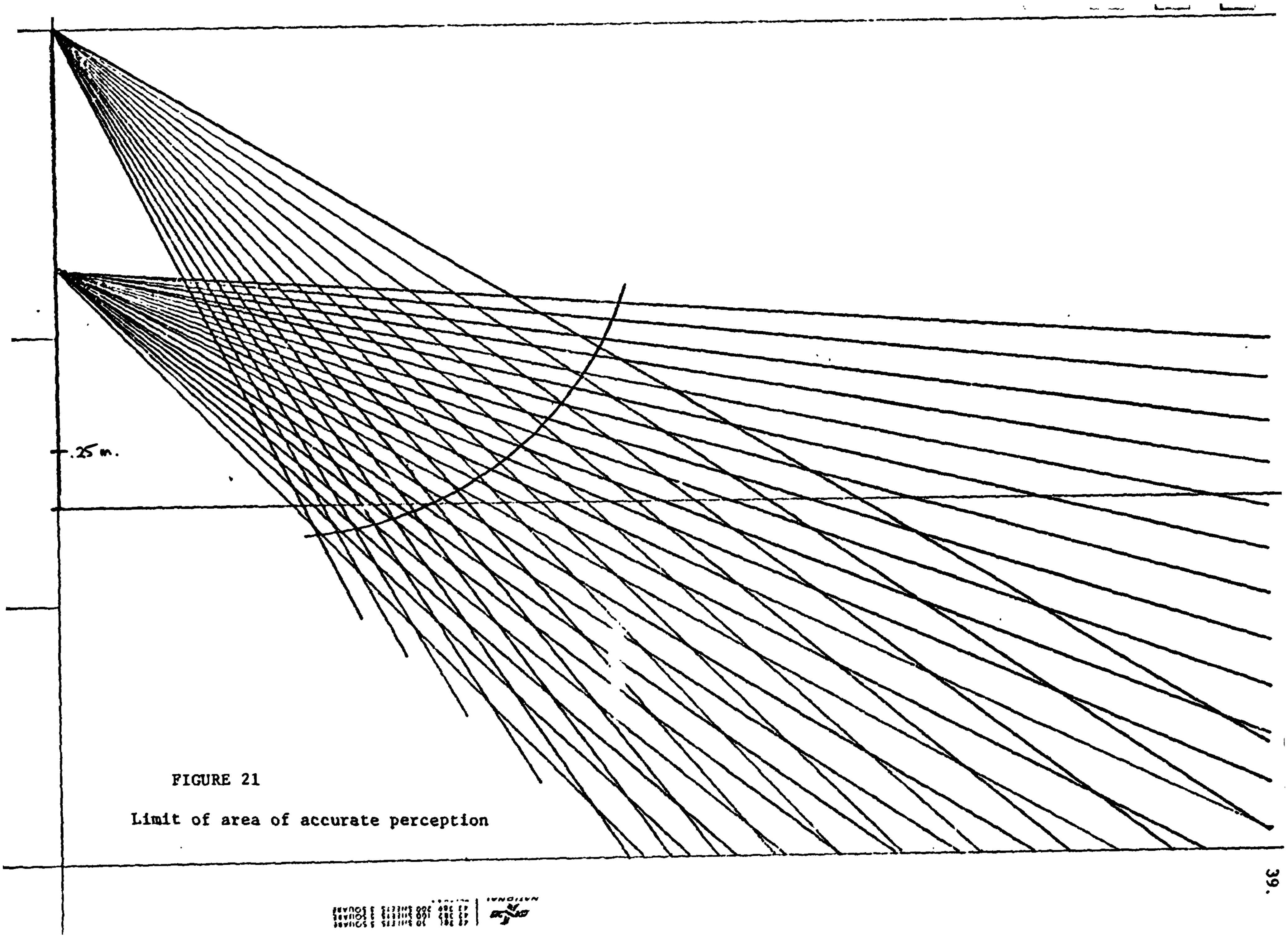

FIGURE 21

Limit of area of accurate perception

the same way that digital communication systems are useful in reducing noise in a signal. Only those features that are large enough to be possible hazards will show up in the data. Any terrain that falls entirely within a single discrimination level is safe and need not be scanned for hazards. This is a big benefit since obstacles are automatically revealed without computational effort.

Having addressed the problem of locating critical heights, the next step is to find a method for determining slopes. The magnitude of a slope is related to the spacing of level changes in the data. A rapid succession of level jumps suggests a steep slope while widely separated jumps mean a much gentler terrain. Unfortunately, the data levels have finite width so that a diagonalized return does not uniquely specify a single slope but, rather, a small range of possible slopes, Figure 22. In order to exactly specify this range of slopes, the upper and lower bounds must be computed. The upper bound is useful because it represents the absolute worst possibility. This is important for a Martian vehicle since no risk can be taken. The lower bound is useful for resolving some ambiguous cases and, thus, providing for better decisions.

Suppose, for instance, that the range of slopes calculated for a particular terrain feature is 25° to 35°. A possible hazard exists since the maximum slope exceeds 30°. However, there is also the possibility that the terrain is safe since the slope could be as low as 25°. This case is ambiguous. Suppose now that slopes of 35° to 45° are estimated for another feature. The upper bound of 45° again indicates a possible hazard. In this case, though, the minimum slope also exceeds 30° indicating that a hazard definitely exists. A simple procedure for calculating the maximum and minimum slope estimates is presented here. Figures 23 and 24 have been included to aid in the explanation of the procedure.

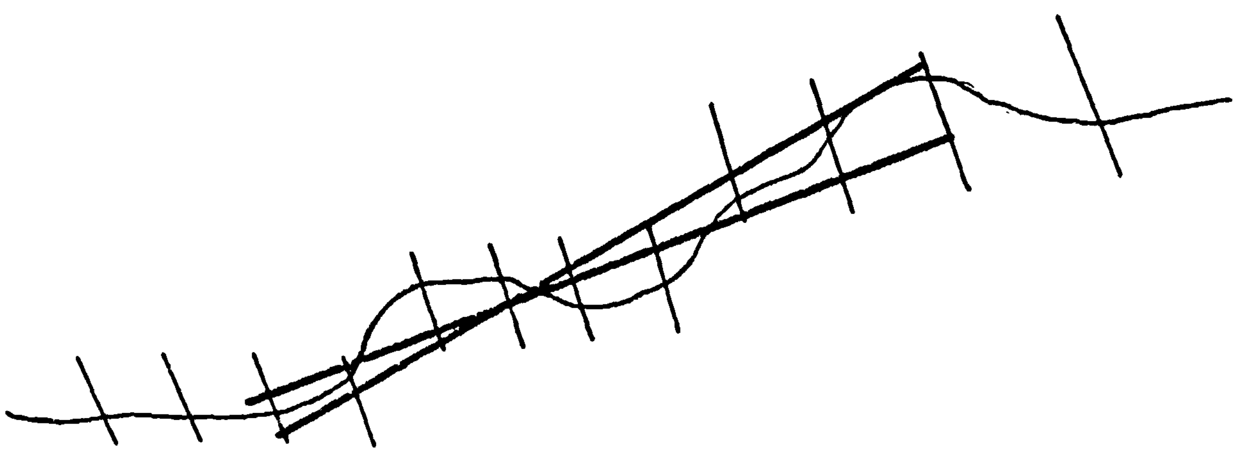

FIGURE 22

Range of slopes possible with given sensor data

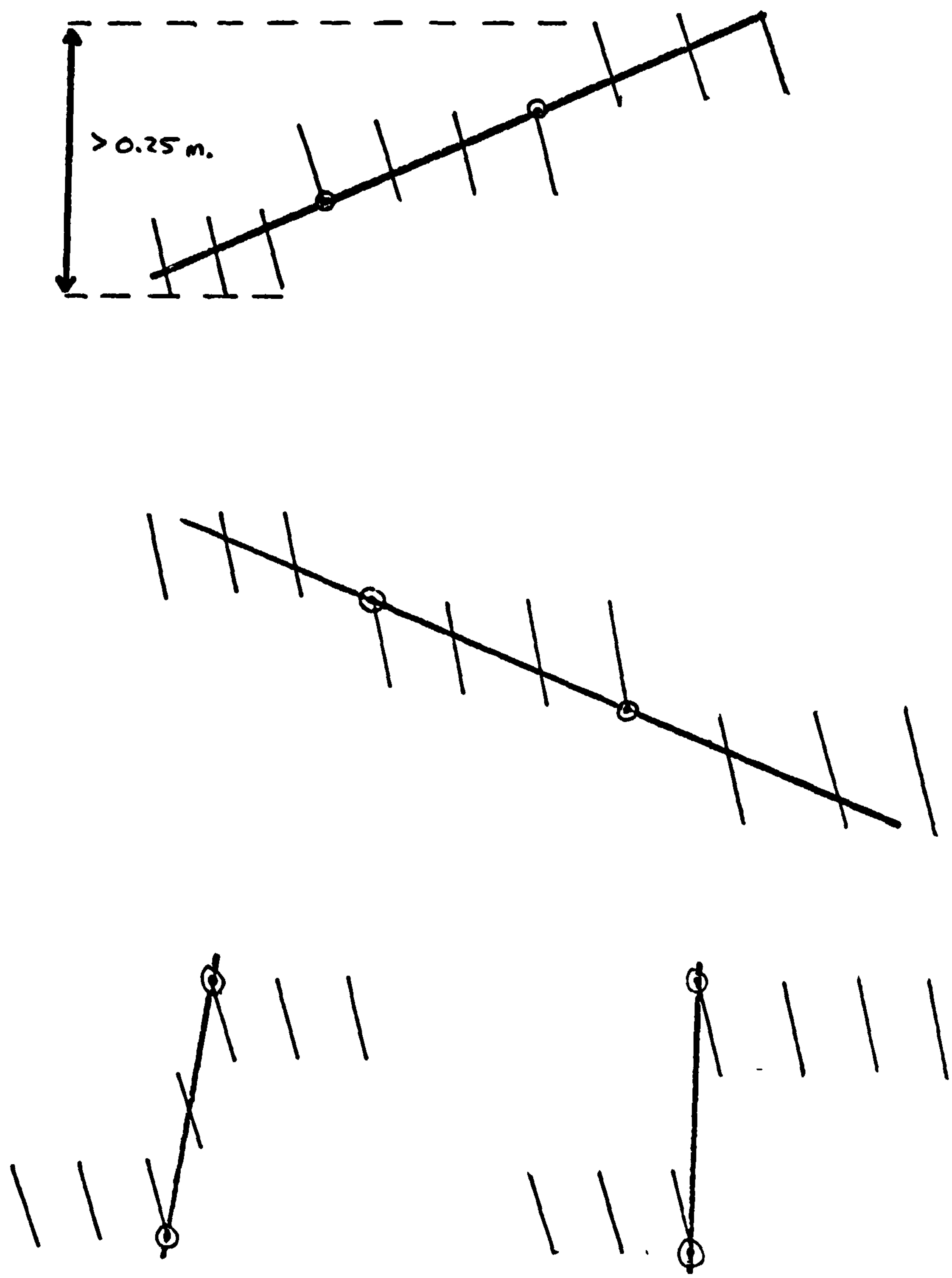

FIGURE 23

Technique for determining maximum slopes

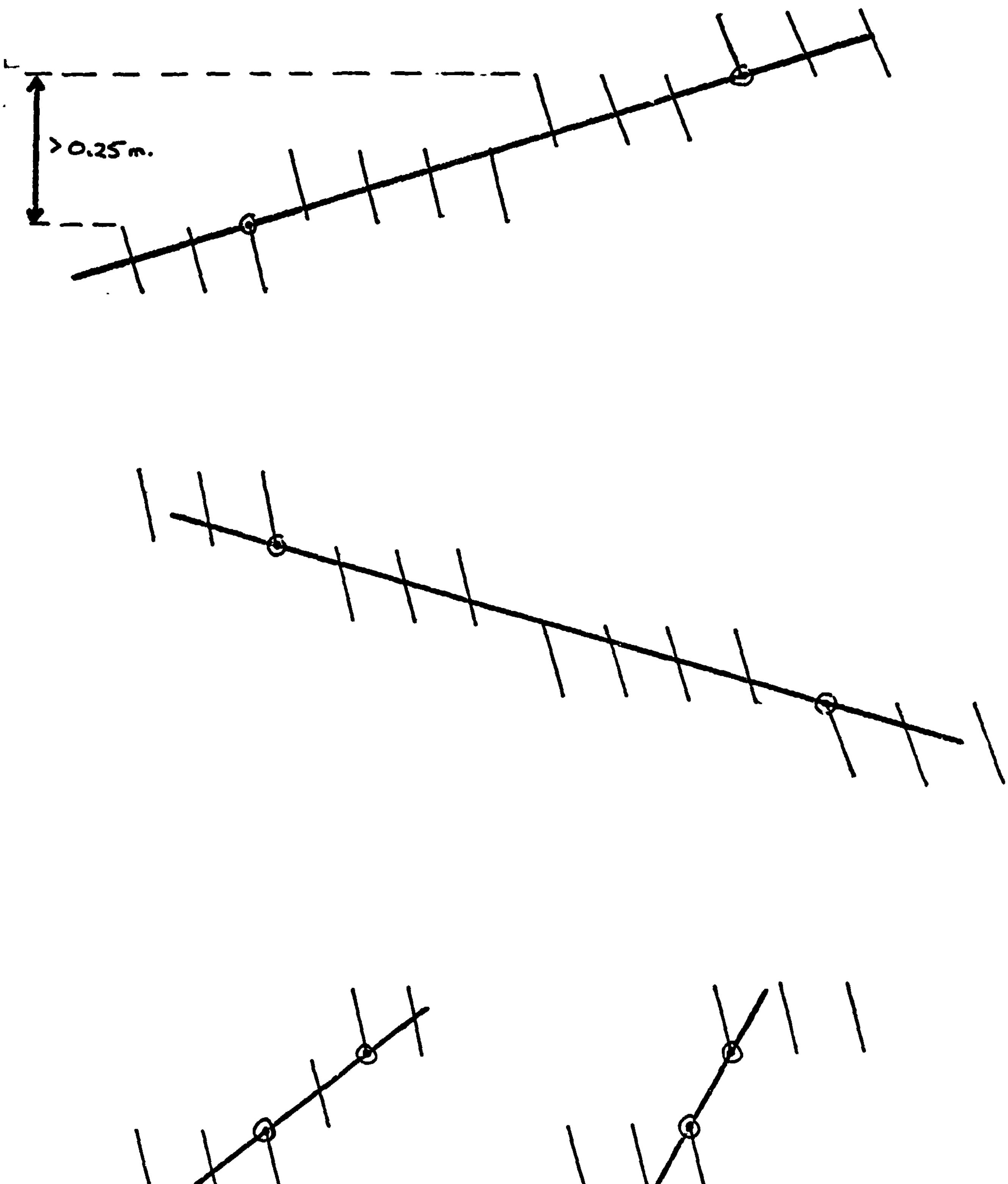

FIGURE 24

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Technique for determining minimum slopes

Maximum Slope

1. Determine that a possible height differential of 0.25 meters exists.

2. Determine the coordinates of the lower endpoint of the first line segment after the first jump and the higher endpoint of the last line segment before the last jump.

3. Compute the slope using these two points.

4. For negative features, select the same line segments but use the opposite endpoints.

5. If multiple or consecutive jumps occur, select the lower endpoint of the line segment before the jump and the higher endpoint of the line segment after the jump.

Minimum Slope

1. Determine that the least possible height differential exceeds 0.25 meters. This is done to make sure that any slope calculated rises above 0.25 meters. Otherwise, the slope is not hazardous regardless of how steep it is.

2. Determine the coordinates of the higher endpoint before the first jump and the lower endpoint after the last jump.

3. Compute the slope between the two points.

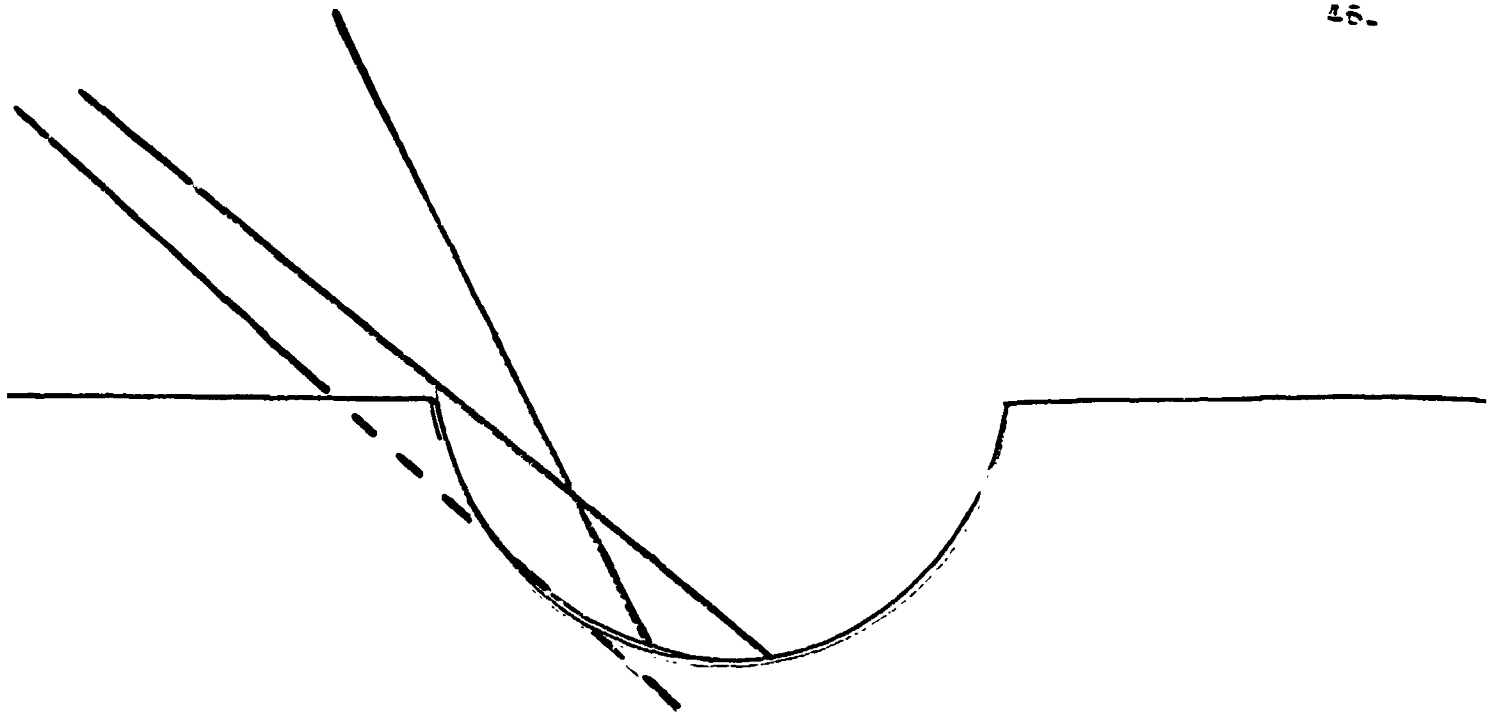
4. For negative features, select the lower endpoint before the first jump and the higher endpoint after the last jump.

5. The procedure does not change for multiple or consecutive jumps.

These methods yield the least and greatest slopes possible that intersect every line segment in the area in question. They are also easily implemented. The locations and magnitudes of level jumps are known from the diagonalized return. The endpoints of all line segments in the array can be computed by geometry and stored for easy access when needed. Since the slope calculations involve just two points, the arithmetic is minimal.

So far, the step and slope criteria for obstacle detection have been considered. The remaining case is the decreased climbing capability when the vehicle pitch exceeds $\pm$ 20°. This test is easily done because the vehicle attitude is readily available from onboard gyros. If the vehicle pitch exceeds 20°, then any positive jumps are assumed impassable. Similarly, negative jumps are impassable if the pitch is less than -20°.

All of the obstacle criteria defined earlier have now been treated. There is, however, another possibility to be considered. It is possible that a laser shot will not be seen by any detector. This can occur if the scattered light is blocked by an obstacle before it reaches a detector. In this case, no data is received and it must be assumed that a deep crevasse exists. Fortunately, missed returns provide some information. Based on the number of consecutive missed returns the size of the hole can be estimated. If the hole is large enough for a wheel to fall into, then the path is unsafe, Figure 25. However, just because the gap is small, safety is not guaranteed. Several missing returns can also signnify a sharp, hazardous drop. To account for this possibility, the difference in terrain height before and after the missed returns is computed, Figure 26. Of course, when the missed returns occur at either end of a scan, the height of the terrain is not known on both sides of the missed data. If the closest laser shots are not seen, then the vehicle is close to a potential obstacle but can no longer see the entire feature. To deal with this case, it is assumed that the whole feature was seen in a previous scan. Since past scans did not detect an obstacle, the terrain is considered safe in spite of missed returns. Missed returns can also occur at the far end of the scan. This possibility raises another important issue. Often a possible obstacle is detected at a distance but there is insufficient information to make a definite decision. In the case of missed returns, a single one at the far end of a scan may signal the leading edge of a crevasse or just a small, traversable depression. An example of another ambiguous case occurs when a distant object is determined to have a range



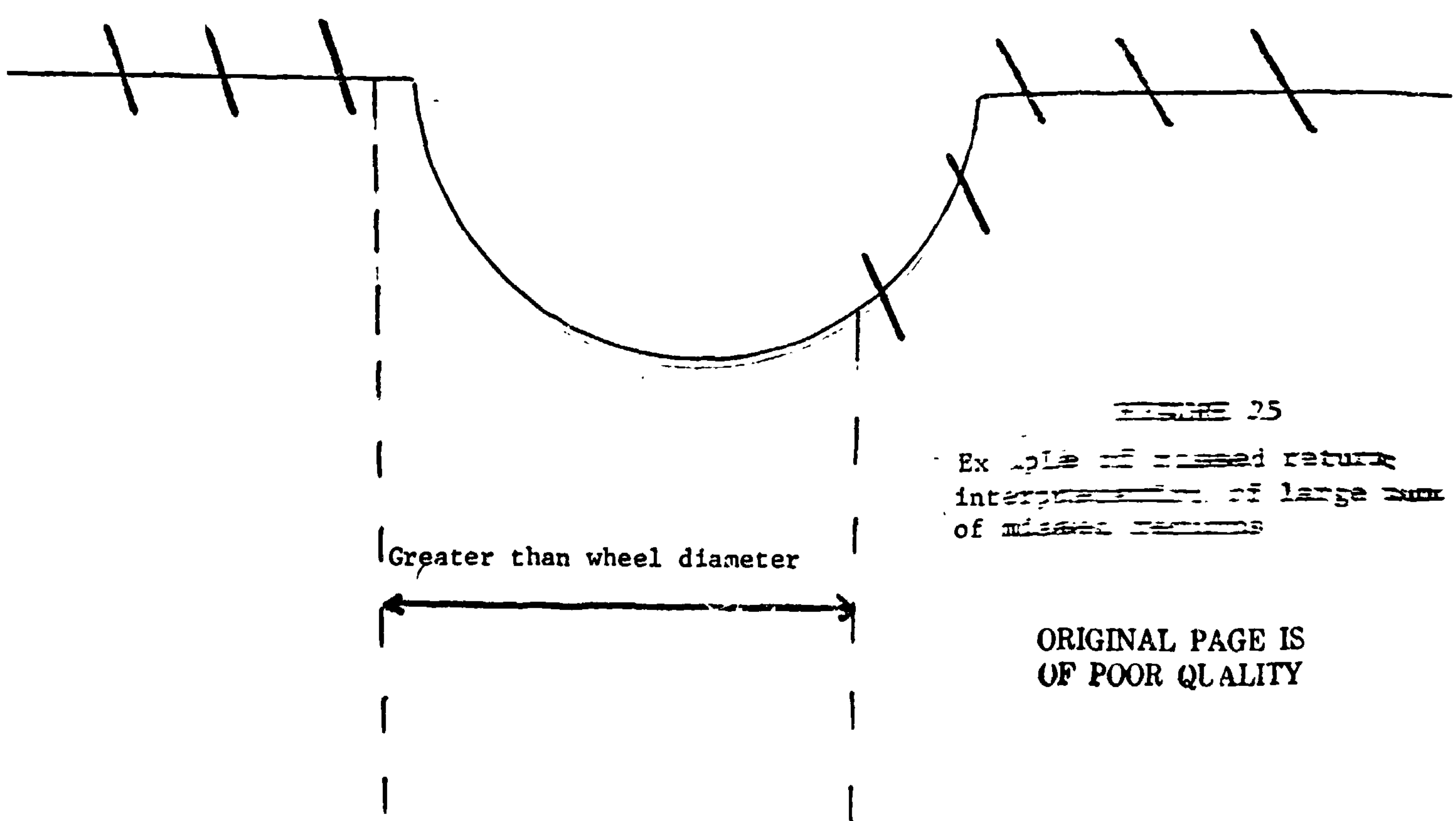


FIGURE 25

Ex[illegible] [illegible] return
inte[illegible] [illegible] large [illegible]
of [illegible] [illegible]

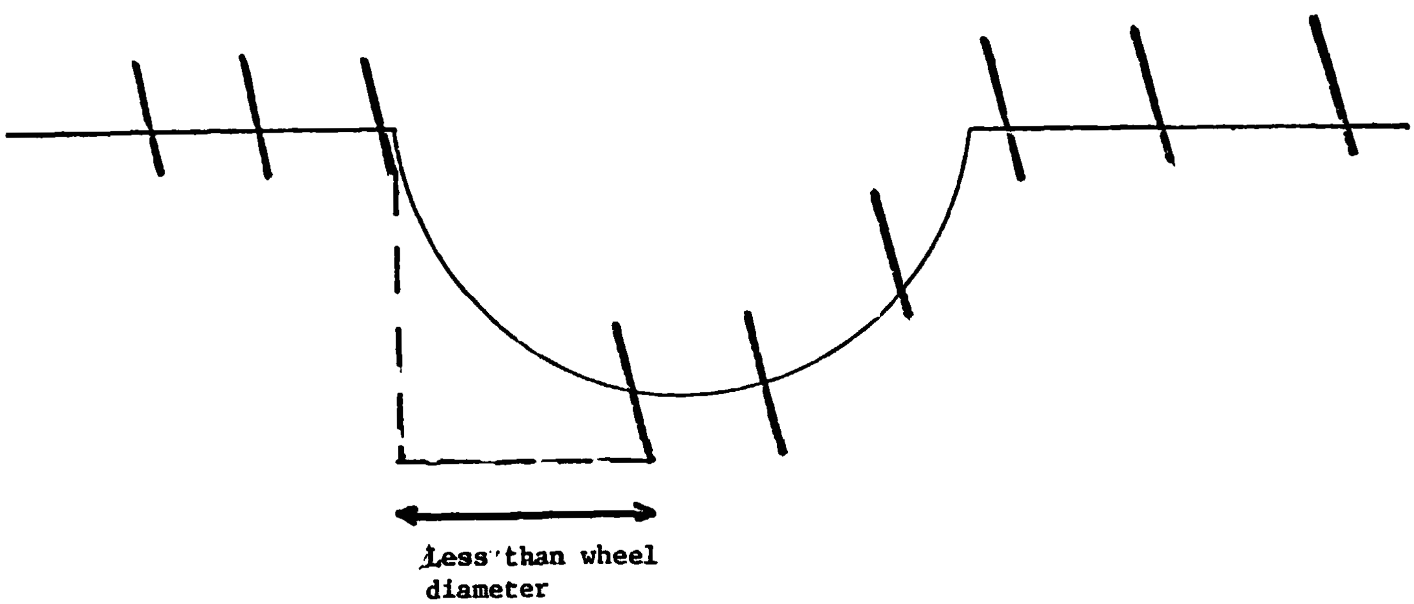


FIGURE 26

Interpretation of small number of missed returns of slopes from 25° to 35°. In both of the above cases,caution should be exercised since the terrain is potentially hazardous. To turn away immediately, however, is not a good idea because many false alarms can occur. This is particularly true due to the poor accuracy of the data at long distances. The obvious solution is to get closer and to take a better look. The R.P.I. vehicle has a scan rate fast enough to give five different views of the same terrain as the vehicle approaches. Taking five scans increases the chances of resolving the ambiguity. Naturally, there is a limit as to how closely the vehicle can safely approach an obstacle. In this system, the limit is set at 1.4 meters. The strategy is, therefore, to approach an obstacle until either a definite decision is made or until the obstacle is within 1.4 meters in range.

Until now, all of the obstacle detection has been done in the vehicle frame of reference. The reason for doing the analysis this way is simplicity. The coordinate transformations required to convert the data from the vehicle to the planet frame require additional calculational effort and time. After that has been done, the benefits of the horizontal quantization levels are lost. However, the step and slope climbing ability are related to gravitation and only have meaning in the planet frame. The solution is to convert all of the computer terrain slopes to the planet frame by simply adding in the vehicle attitude. This is much simpler and faster than doing the transformation before the slopes are computed.

The hazard detection algorithm is now complete and a general flow chart appears in Figure 27.

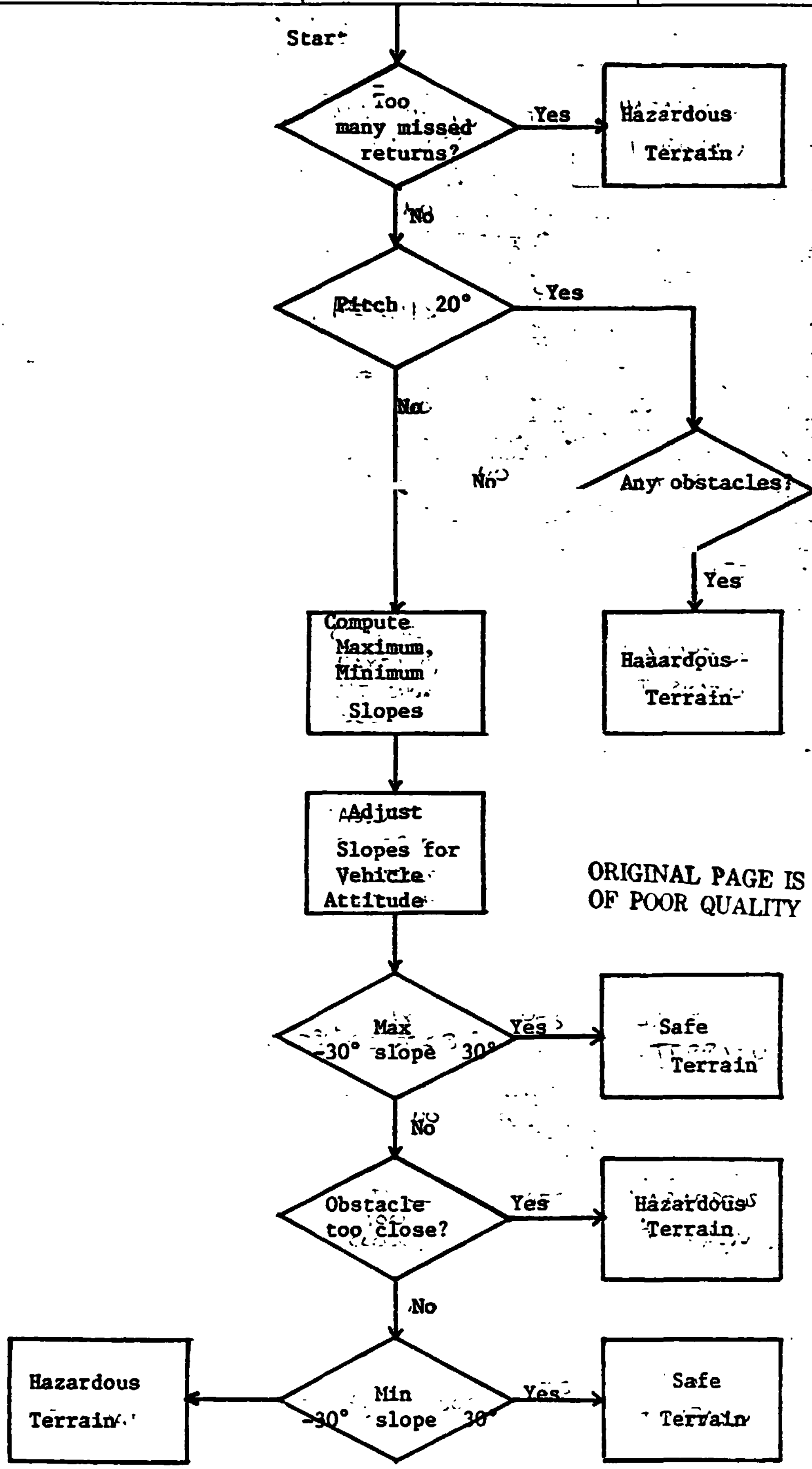


FIGURE 27
General flowchart for hazard detection

V. SIMULATION PACKAGE

The multi-laser/detector triangulation sensor and the accompanying hazard detection algorithm are to be tested using the R.P.I. dynamic simulator[4]. The dynamic simulator is the result of several years of effort and accurately represents the scanning, decision making, and motion of the actual vehicle on specified terrain surfaces. The user can choose from among a number of available general terrain surfaces including slopes, hills, and sine waves. Discrete obstacles such as boulders, craters, and steps may be added to the general terrain surface. There is also the provision for simulating rubble and small rocks on the surface as a noise function.

The user may also choose from a variety of sensors and is free to specify the placement, size, and geometry of each. There is a choice of data processors and path selection algorithms to interface with the various sensors. The measurements made by the sensors can also be contaminated by noise if so desired. The user can also control the physical dimensions and dynamics of the vehicle.

After the user specifies the initial and target locations, the simulation package takes over. Sensor scans are taken at user prescribed intervals after vehicle attitude information from the gyro subroutine adjusts the sensor position position. A terrain model is developed and the best path is selected based on the vehicle's position relative to the target and the surrounding hazards. Control then passes to the motion routine and the vehicle is moved at a rate and for a duration given by the user. The cycle then repeats after this point.

The simulation terminates when either the target is reached, the allotted time is exceeded, or the vehicle finds no safe paths available. At this time, the performance is evaluated based on path length, trip duration, and the number of close encounters with hazards. Finally, maps are printed out showing the terrain and the vehicle trajectory.

VI. SIMULATIONS AND RESULTS

Four groups of simulations have been conducted each designed to test the sensor's ability to detect various obstacles under various conditions. These are summarized in the table below.

Simulations Performed

I. Vertical Steps

- A. 0.2 meters high
- B. 0.3 meters high
- C. 0.4 meters high

II. Smooth Slopes

- A. Twenty degrees
- B. Twenty-five degree magnitude
  1. Positive slope with 15 laser, 20 detector system
  2. Positive slope, same sensor but field of view aimed closer
  3. Negative slope, original system
- C. Thirty degree slopes
  1. Original 15 laser, 30 detector system
  2. 25 laser, 30 detector system
  3. 32 laser, 40 detector system

III. Sine Waves

- A. 0.25 meter amplitude, 6.0 meter period
- B. 0.3 meter amplitude, 6.0 meter period
- C. 0.4 meter amplitude, 6.0 meter period

IV. Boulder and Crater Field

In the first group of simulations, vertical steps of various sizes are placed in the vehicle's path. The purpose of these tests is to determine the vehicle's ability to detect changes in terrain elevation. When a change in height of 0.25 meters is detected, the slope of the leading edge of the step is computed. No calculations are done for small steps. The smallest step size worth considering is 0.2 meters. According to the algorithm, an object must create a change of two levels in the diagonalized return before it can be considered hazardous. A drawing of the 15x20 array shows that this does occur when a 0.2 meter step is within a 1.4 meter range, Figure 28. The simulation verifies this. Initially, only zeroes and ones appear in the diagonalized return and the terrain is considered safe. It is not until the scan at one meter range that returns occur in the second level. A slope of 98° is calculated for the leading edge and the feature is declared hazardous, Figure 29. Ideally, the path should have been declared safe since the obstacle is below the 0.25 meter threshold. It is the discreteness of the data, not a defect in the data processor that prevents making a more accurate decision. Given the data received the step could have been as high as 0.35 meters or as little as 0.1 meters. Since the error is due to the finite width of the quantization levels, making them smaller is the best way to improve performance.

Steps of greater height are also considered. Obviously, these will be detected as hazardous. What is of interest is to note at what range the decision to avoid the obstacle is made. Due to myopia, the vehicle will see only larger objects at a distance and the smaller ones up close. For a 0.3 meter step, a possible obstacle is detected at 2.2 meters range. However, the data are not good enough at that point to know for certain that a hazard exists. The criterion for such a decision is that the minimum possible change in elevation be at least 0.25 meters. This never happens, though, and the vehicle continues to approach until it reaches 1.0 meters range. Even though the ambiguity is not resolved, the vehicle must turn due to the close proximity of the obstacle.

The last run in this group is a 0.4 meter step. A possible hazard is detected at 2.5 meters range. Again, the data is not good enough to

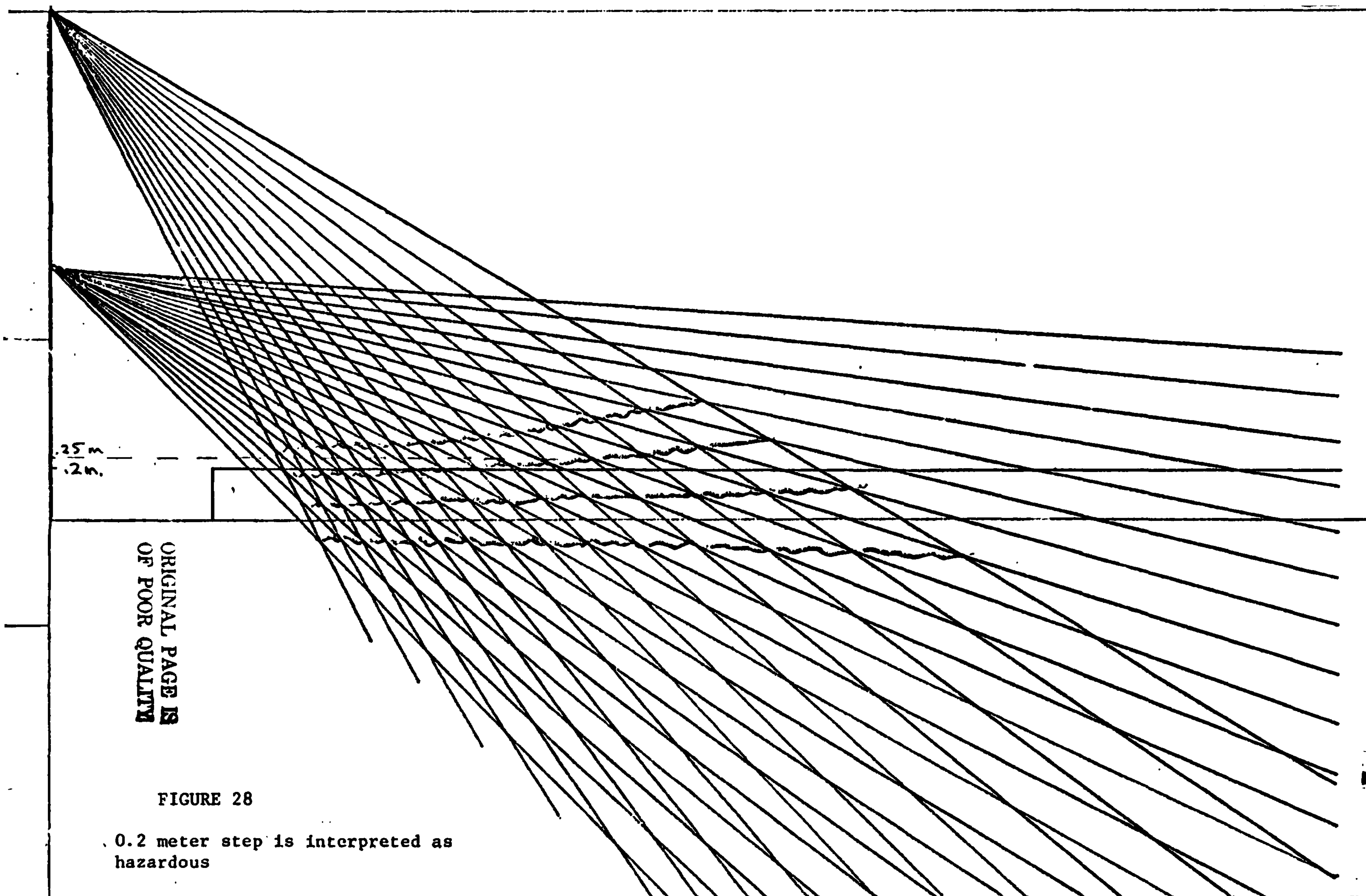


FIGURE 28

0.2 meter step is interpreted as hazardous

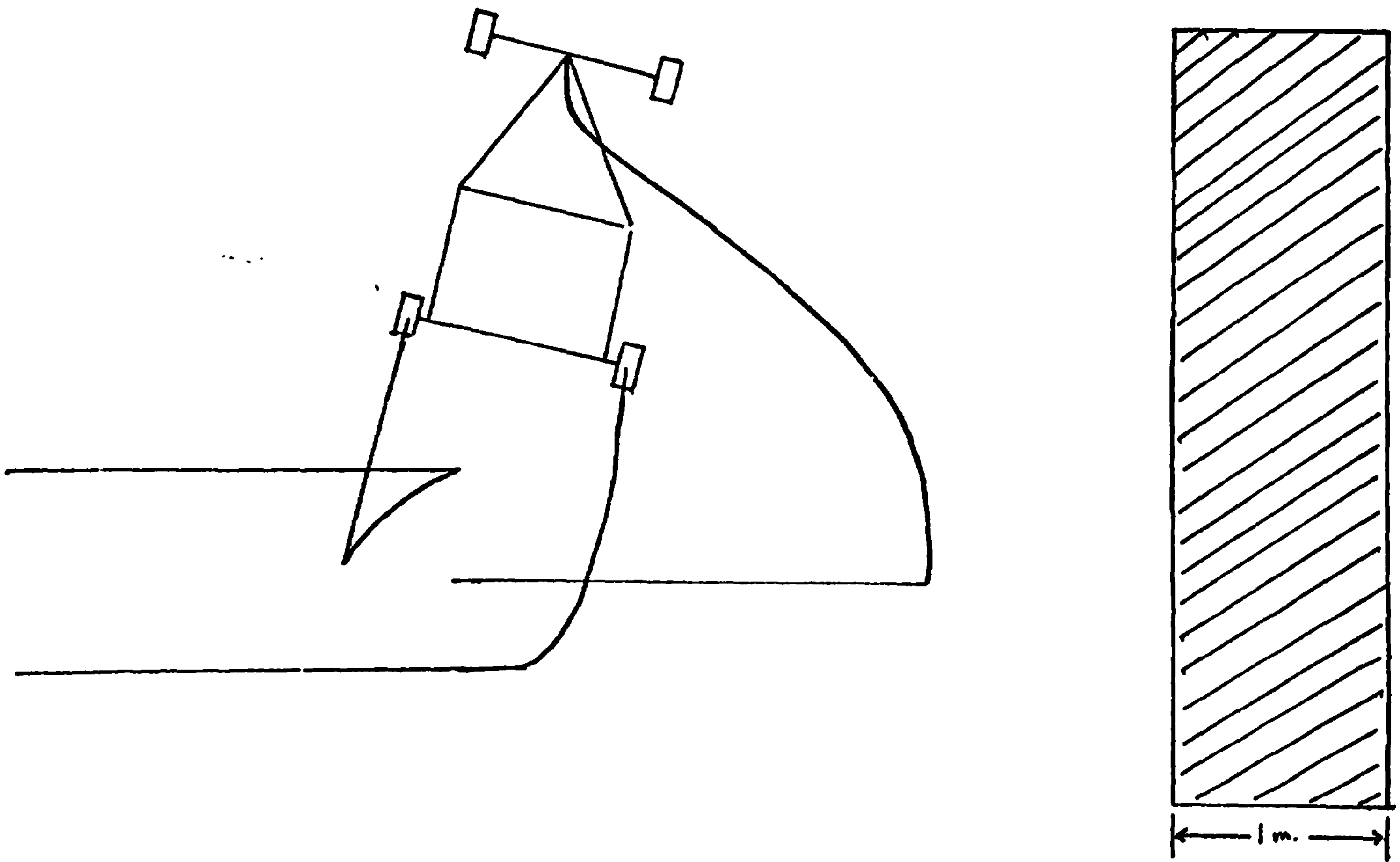


FIGURE 29

Trajectory of vehicle encountering 0.2 meter step make a decision. The vehicle proceeds until at 1.9 meters range a minimum step of 0.25 meters is detected. The calculated maximum and minimum slopes are 105° and 60°, respectively. Steps whose heights exceed 0.4 meters will be declared definitely hazardous on the first scan. This would occur at about 2.5 meters in range. In summary, anv obstacle at least 0.2 meters in height is avoided by the vehicle. This includes features from 0.2 to 0.25 meters high that in reality are safe. Large obstacles are seen and avoided at greater ranges than smaller obstacles. The limitations stem from the quantization error inherent in the system. The best way to improve performance is to increase detector density by adding more detectors and reducing the field of view of the individual detector.

The next group of simulations tests the ability of the algorithm to estimate the magnitudes of smooth slopes. The first run at 20° is used to demonstrate the performance for an easy case. The vehicle begins on horizontal ground and approaches the slope head on. At 1.8 meters enough information is available to estimate a maximum slope of 39°. As the vehicle approaches, the estimates improve until at the 1.0 meters range the slope is estimated to lie between 17° and 25°, Figure 30. The slope calculations for the off center azimuths indicate less severe slopes since those gradients are not as steep. For instance, in the 30° azimuth the true gradient is 17.3° and the processor computes the maximum slope as 18°. Also of note is that the minimum slope calculations are generally more accurate than maximum slopes. The reason is that minimum slopes must be computed over longer ranges. This helps average out some statistically bad data.

As the vehicle continues to approach the 20° slope, the estimates do not improve appreciably. The maximum slope never exceeds 25°, though,

DIAGONALIZED RETURN

AZIMUTH / LASER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15	0	1	1	2	2	3	3	3	3	3	2	2	1	1	0
14	0	1	1	2	2	2	3	3	3	2	2	2	1	1	0
13	0	0	1	2	2	2	2	2	2	2	2	2	1	0	0
12	0	0	1	1	2	2	2	2	2	2	2	1	1	0	0
11	0	0	1	1	1	2	2	2	2	2	1	1	1	0	0
10	0	0	0	1	1	2	2	2	2	2	1	1	0	0	0
9	0	0	0	1	1	1	1	2	1	1	1	1	0	0	0
8	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
7	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0
6	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0
5	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
4	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

AZIMUTH ANGLE -40. DEGREES

```
MAX SLOPE(DEG)   21.
MIN RANGE(M)      1.6
MAX RANGE(M)      2.1
```

AZIMUTH ANGLE -30. DEGREES

```
MAX SLOPE(DEG)   18.
MIN RANGE(M)      1.4
MAX RANGE(M)      1.9
```

AZIMUTH ANGLE -20. DEGREES

```
MAX SLOPE(DEG)   24.     21.
MIN RANGE(M)      1.3     1.7
MAX RANGE(M)      1.6     2.3

MIN SLOPE(DEG)   17.     16.
MIN RANGE(M)      1.2     1.6
MAX RANGE(M)      2.5     2.5
```

AZIMUTH ANGLE -10. DEGREES

```
MAX SLOPE(DEG)   19.     23.
MIN RANGE(M)      1.2     1.7
MAX RANGE(M)      1.6     2.1

MIN SLOPE(DEG)   17.
MIN RANGE(M)      1.1
MAX RANGE(M)      2.3
```

AZIMUTH ANGLE 0. DEGREES

```
MAX SLOPE(DEG)   25.     22.
MIN RANGE(M)      1.2     1.6
MAX RANGE(M)      1.5     2.1

MIN SLOPE(DEG)   17.
MIN RANGE(M)      1.1
MAX RANGE(M)      2.3
```

AZIMUTH ANGLE 10. DEGREES

```
MAX SLOPE(DEG)   19.     23.
MIN RANGE(M)      1.2     1.7
MAX RANGE(M)      1.6     2.1

MIN SLOPE(DEG)   17.
MIN RANGE(M)      1.1
MAX RANGE(M)      2.3
```

AZIMUTH ANGLE 20. DEGREES

```
MAX SLOPE(DEG)   24.     21.
MIN RANGE(M)      1.3     1.7
MAX RANGE(M)      1.6     2.3

MIN SLOPE(DEG)   17.     16.
MIN RANGE(M)      1.2     1.5
MAX RANGE(M)      2.5     2.5
```

AZIMUTH ANGLE 30. DEGREES

```
MAX SLOPE(DEG)   18.
MIN RANGE(M)      1.4
MAX RANGE(M)      1.9
```

AZIMUTH ANGLE 40. DEGREES

```
MAX SLOPE(DEG)   21.
MIN RANGE(M)      1.6
MAX RANGE(M)      2.1
```


FIGURE 30
Diagonalized return and slope estimates for 20° slope

and the vehicle is allowed to climb. As this occurs, a steadily decreasing slope magnitude is perceived. After correcting the slope estimates for the vehicle attitude, they are similar to the estimates obtained on level ground, demonstrating that accurate estimates can be made when the vehicle has an arbitrary pitch. When the vehicle pitch approaches that of the slope, the perceived slope is so small that no potential hazards are detected, Figure 31. In this situation there is less that can be said about the terrain inclination. The reason is that the change in terrain elevation seen by the vehicle is less than 0.25 meters. Therefore, no slope estimate is obtained. In this case, the vehicle assumes that if its inpath slope is less than 20°, any terrain that lies ahead is safe. The vehicle then proceeds to climb completely onto the slope at which point it sees flat terrain everywhere. In this case, the assumption made as to the safety of the terrain is correct. The program ignores other possibilities, though, where the logic breaks down. Suppose the vehicle is traveling across the face of a 30° slope, Figure 32. The inpath slope is 0° while the crosspath slope is 30°. If a small terrain feature appears on the vehicle's high side, the path in which it lies is considered safe. The reason is that as in the case above,the vehicle inpath pitch is less than 20°. However, if the vehicle chooses that path, it will be traveling up a gradient in excess of 20°. The vehicle can tolerate absolutely no obstacles in this case and the terrain is actually hazardous. A simpler example involves the vehicle climbing a 40° slope at a 45° angle. The inpath gradient is 28° and safe. Suppose the vehicle wants to make a -45° turn. The scan shows flat terrain and the turn is allowed. In reality, the path chosen has a 40° gradient. To correct this problem, the vehicle roll must also be accounted for. From pitch and roll information the plane

DIAGONALIZED RETURN

LASER \ AZIMUTH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
15	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1
14	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1
13	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1
12	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1
11	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1
10	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1
9	1	1	1	1	2	2	2	2	2	2	2	1	1	1	1
8	1	1	1	1	2	2	2	2	2	2	2	1	1	1	1
7	1	1	1	1	2	2	2	2	2	2	2	1	1	1	1
6	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
5	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
4	1	1	1	1	1	1	2	2	[illegible]	1	1	1	1	1	1
3	0	1	1	1	1	1	1	1		1	1	1	1	1	0
2	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0

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FIGURE 31

Diagonalized return for 20° slope, vehicle pitch 10.4°

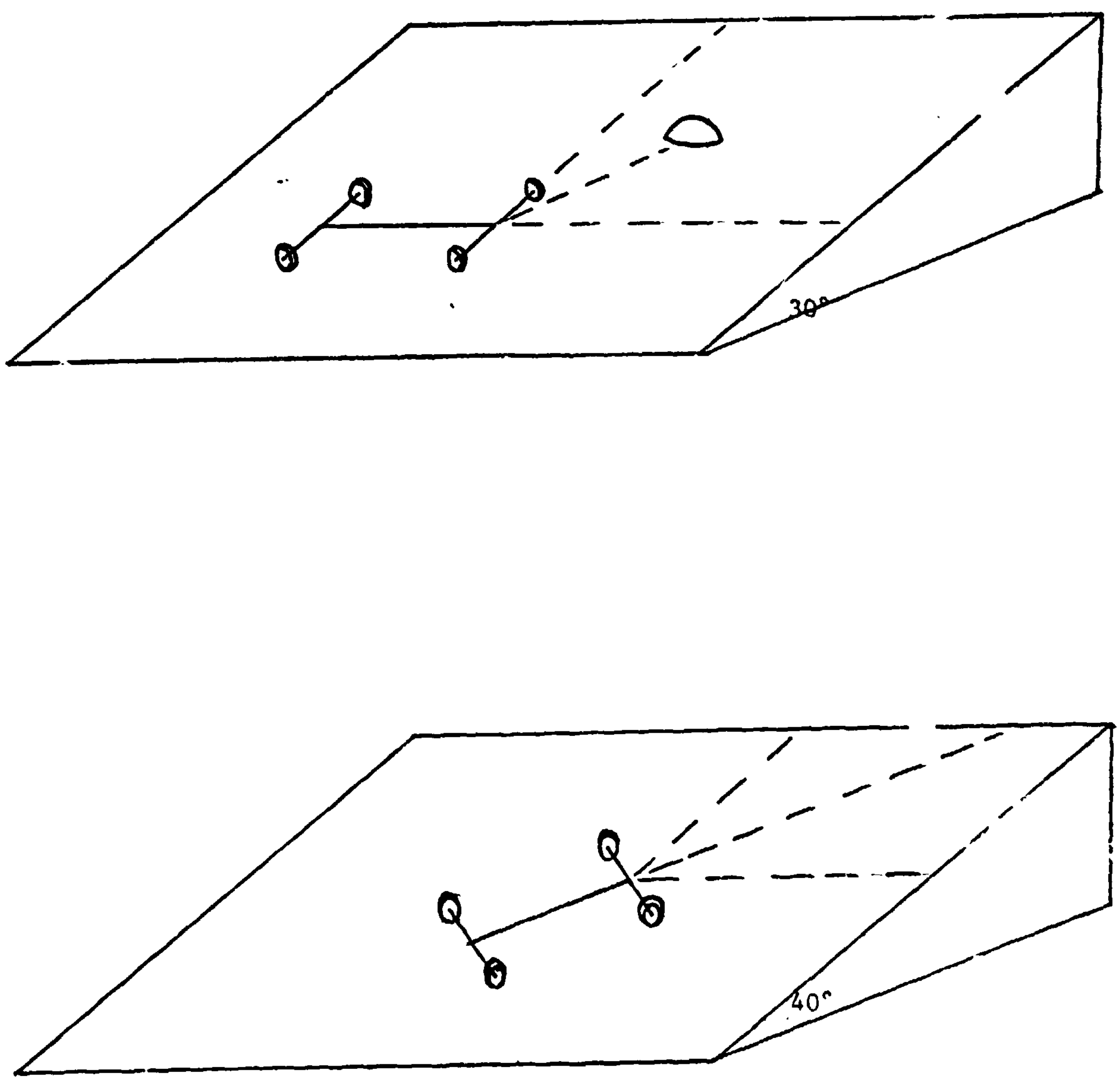

FIGURE 32

Examples demonstrating importance of incorporating roll information in patch inclination estimates in which the vehicle lies can be determined. It is then an easy matter to find the inclination in any azimuthal direction by taking the directional derivative. In this way, the estimated slopes can be properly corrected for vehicle attitude.

To test the vehicle under more challenging conditions, a 25° slope is attempted. The first slope estimates of 41° occur at 1.8 meters range. As with the 20° slope, the estimates improve until the vehicle is within 1.0 meters. At this range the computed slope range is from 21° to 34°. This range of slopes is greater than for the 20° case. Steeper slopes are generally predicted less accurately than gentler ones. The reason can be determined by observing the data for both cases, Figure 33. With steep slopes the level jumps occur closer together and allow a greater range of slopes. Furthermore, negative slopes are estimated more accurately than positive ones. This happens because negative slopes are nearly parallel to the laser shots, Figure 34, and allow only a very small slope variation. A test on a -25° slope reveals that the slope estimates have a much smaller variance than in the 25° case. This does not mean that, in general, negative terrain is perceived more accurately than positive terrain. This is only a special case of smooth slopes. The data in the lower area of the terrain is very poor and should result in poor estimates for arbitrary negative obstacles.

Returning to the 25° simulation, the computed slope range of 21° to 34° in the center azimuth forces the vehicle to change course. It must climb the slope at an angle so that the gradient is less steep. Once the vehicle is completely on the slope, it sees level ground and is able to resume its original heading, Figure 35. It is disappointing to see that a

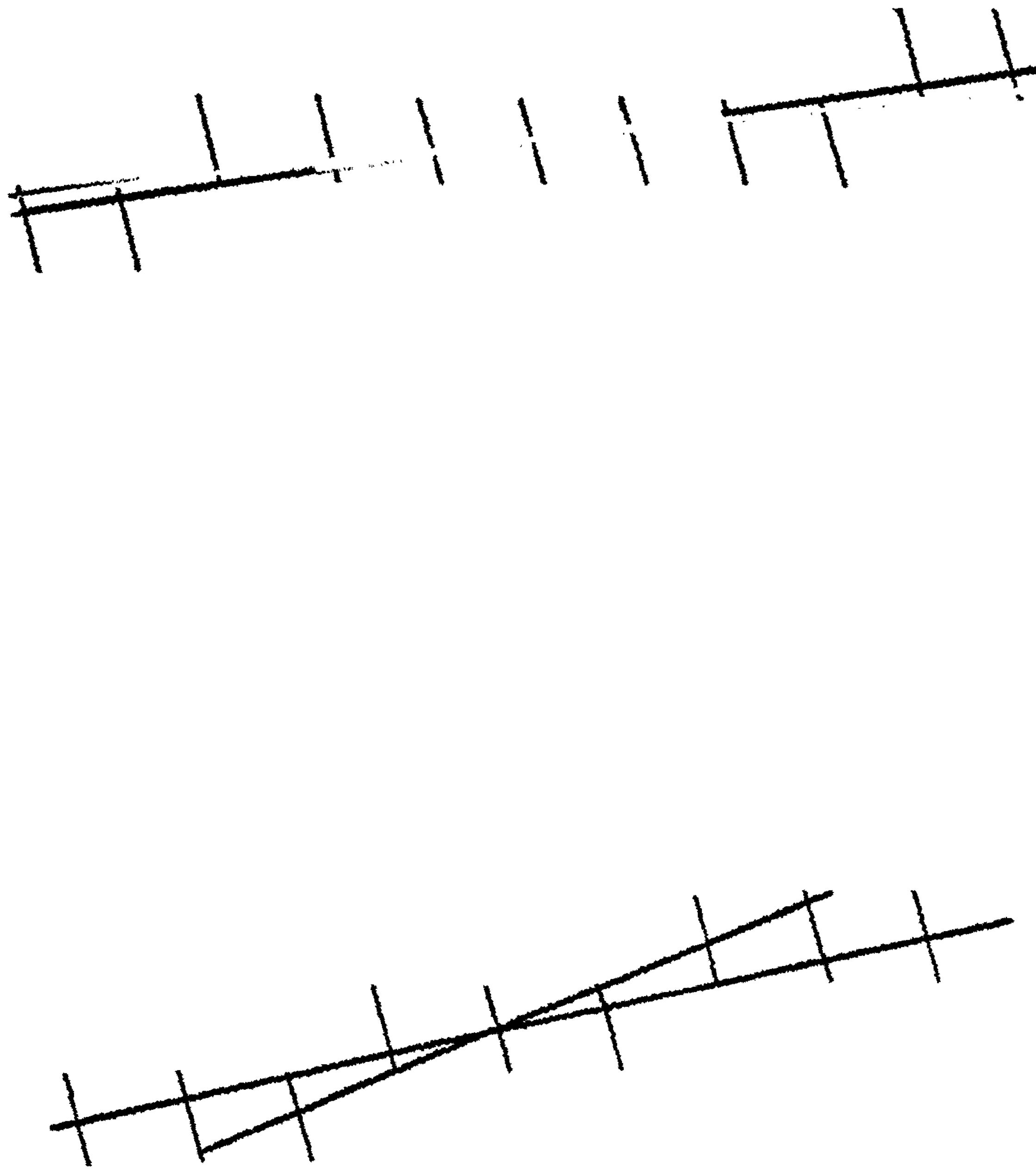

FIGURE 33

Example of greater deviations possible with steeper slopes

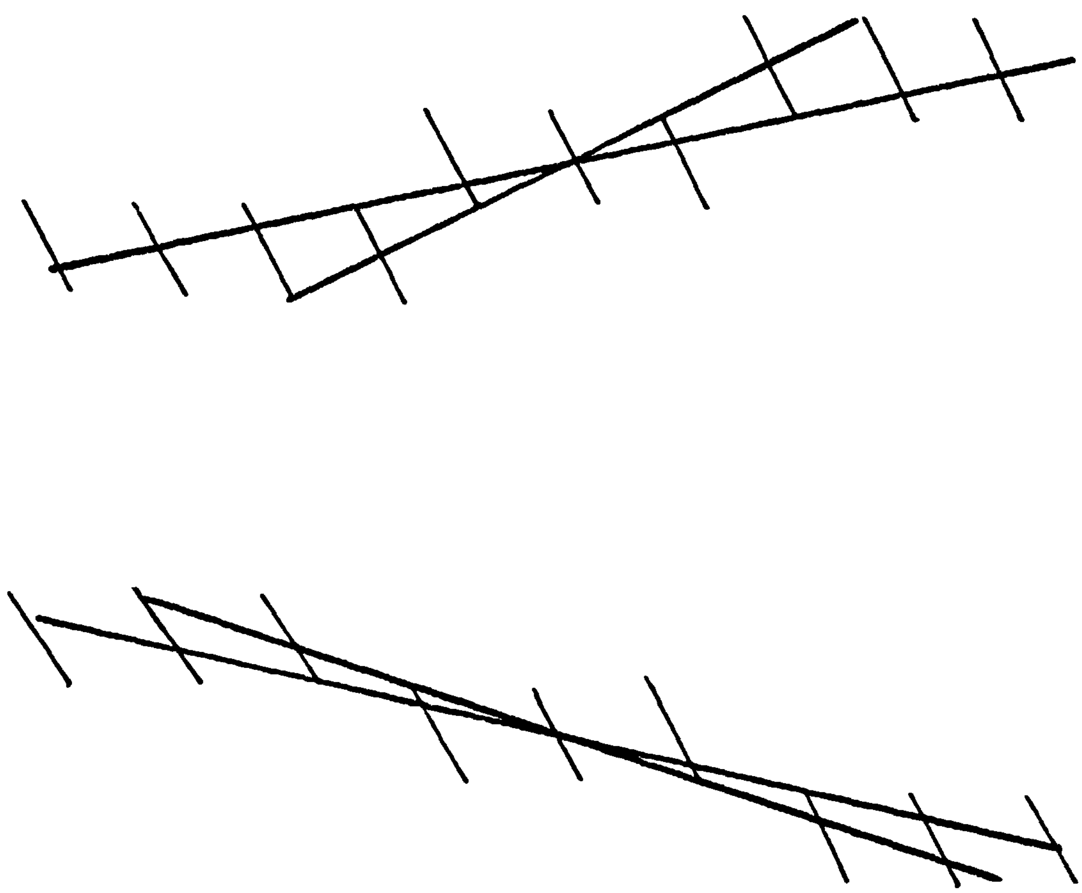

FIGURE 34

Slope estimates experience ~~smoother~~ deviations in the negative case

25° slope cannot be climbed head on. This would be possible if the data were made more accurate. One way of doing this is to move the field of view in closer. This concentrates the same number of laser shots into a smaller area. To test the effectiveness of such a modification another 25° run is done with the 15x20 array. This time the field of view is moved in so that the first laser pulse strikes level ground at 0.6 meter as opposed to 1.0 meter previously. As a result, the vehicle must now approach even closer to get a good view. With the modified array, no slopes are calculated until the vehicle is within 1.0 meters. At this point the initial estimate is 34° as compared to 41° for the initial estimate for the first case. However, that 41° estimate was made at 1.8 meters range. The previous system predicted a slope of 21° to 34° at the 1.0 meter range. This is the same maximum slope predicted by the modified array at the same distance. The estimate from the modified array improve as it approaches while the original system gave practically the same estimates. At 0.6 meter the computed slope is 31°. This is 3° better than the original system. Hence, the vehicle must still turn since the 30° threshold is exceeded. The conclusion is that, at least for such slopes, no noticeable improvement results from moving the field of view in closer.

Returning to the original 15x20 system, a 30° slope is now attempted. Of course, there is no way that the vehicle can climb this slope head on. The simulation is, therefore, done with the vehicle attempting to climb at a 40° angle. Systems with 25 lasers x 30 detectors and 32 lasers x 40 detectors are also tested on the same path as the 15x20. This is done to determine the effectiveness of increasing data density and accuracy. The results are shown in Table 1.

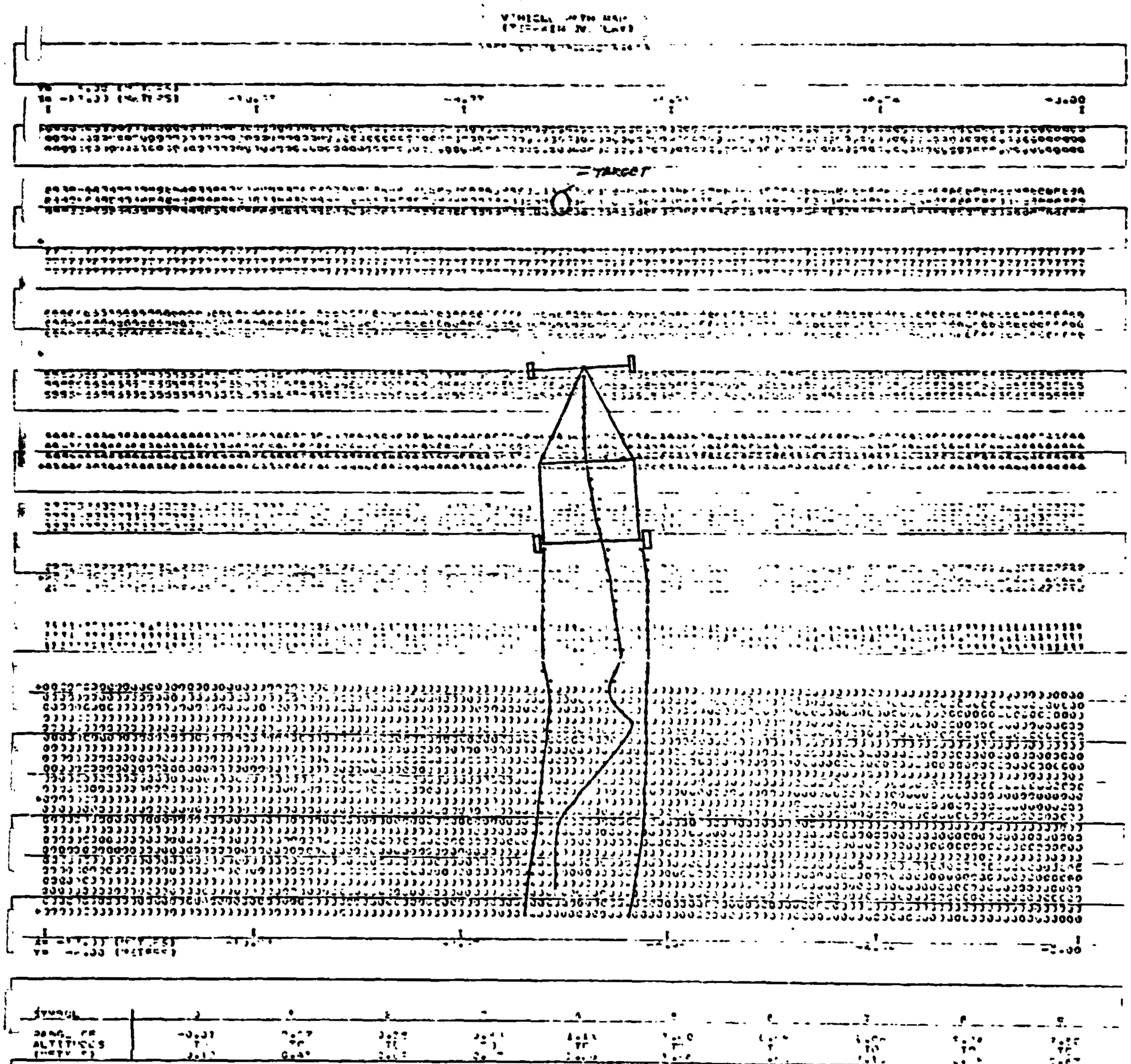

FIGURE 35

Vehicle trajectory 25° slope

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TABLE 1

COMPARISON OF DIFFERENT SENSOR SYSTEMS VIEWING 30° SLOPE

Range to start of slope (m.)	Slope estimates (degrees) 15x20			25x30						32x40						
1.8			86	43	85	38	83			43	40	40	84	38		
			-	26	25	26				26	29	25	25			
1.5	45	84		42	43	84	40			47	44	33	32	40	83	
	28			28	27	27				28	27	25	27			
1.2	32	43	82	52	30	83	42	41		33	37	35	34	34	34	41
	23	29		28	27	29	26			27	27	26	26	27	26	
1.0	54	32	44	38	39	37	45	44	43	38	30	32	37	36	31	36
	25	24		28	29	28	29	28		28	28	27	27	28	27	
0.7	51	47	32	39	38	32	32	45		34	33	36	35	32	33	
	28	26		30	27	28	27			30	28	30	29	28		
0.4	48	43		33	33	33	34	35		35	33	31	32	32	33	
	26			28	28	28	29			29	28	28				

Two sets of slope estimates are given of each location for each system. The maximum estimates are on the upper line and the minimum estimates are on the lower line.

Multiple estimates are given of each location because the estimates correspond to different sections of the same terrain. They are arranged in increasing order of range.

The effect of additional lasers and detectors is quite noticeable. With all three systems, the maximum slope estimates always overestimate the true slope while the minimum estimates always underestimate. The difference is that the amount of variation in the estimates is greatly decreased when greater data density is used. Unfortunately, even the finest array gives some statistically bad data, even at close range. However, the probability of receiving statistically bad data is much lower than with the 15x20. A common way of dealing with statistically bad data is to use filtering or smoothing techniques. This usually requires many measurements of the same signal or object. Even though the laser scanner does not generate a large quantity of data, some first approximations can be made. The higher order systems, such as 25x30 make several slope estimates over a short section of terrain. If the terrain is assumed not to vary greatly over small distances, then some smoothing can be done. As an example, Figure 36 lists slope estimates obtained from a 25x30 sensor system scanning a 30° slope. All of the estimates are based on data from a single scan. Each estimate represents only a small section of the slope and the estimates are printed in order of increasing range. In the -60° azimuth, the 39° estimate is the closest and is based on the most accurate data. However, it is also the least accurate estimate of the five calculated in that azimuth. The other four estimates are very consistent and cast doubt on the validity of the 39° estimate. Furthermore, the range of the 39° estimate partially overlaps the range of the adjacent 32° estimate. For these reasons, the inconsistent estimate should not be counted as heavily.

In this example, the slope is still hazardous even if the 39° estimate is ignored. There may be other situations in which this technique would have a greater effect.

DIAGONALIZED RETURN

AZIMUTH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
LASER															
25	***	***	***	***	***	***	***	5	3	2	0	0	0	0	0
24	***	***	***	***	***	***	6	5	3	2	0	0	0	0	0
23	***	***	***	***	7	7	6	4	3	1	0	0	0	0	0
22	7	8	8	8	7	6	5	4	3	1	0	0	0	0	0
21	7	7	8	7	7	6	5	4	3	1	0	0	0	0	0
20	7	7	7	7	7	6	5	4	2	1	0	0	0	0	0
19	6	7	7	7	6	6	5	3	2	1	0	0	0	0	0
18	6	7	7	7	6	5	4	3	2	0	0	0	0	0	0
17	6	6	6	6	6	5	4	3	2	0	0	0	0	0	0
16	6	6	6	6	6	5	4	3	1	0	0	0	0	0	0
15	5	6	6	6	5	5	4	3	1	0	0	0	0	0	0
14	5	5	6	5	5	4	3	2	1	0	0	0	0	0	0
13	5	5	5	5	5	4	3	2	1	0	0	0	0	0	0
12	4	5	5	5	4	4	3	2	1	0	0	0	0	0	0
11	4	5	5	4	4	3	3	2	1	0	0	0	0	0	0
10	4	4	4	4	4	3	2	1	0	0	0	0	0	0	0
9	4	4	4	4	3	3	2	1	0	0	0	0	0	0	0
8	3	4	4	4	3	3	2	1	0	0	0	0	0	0	0
7	3	3	3	3	3	2	2	1	0	0	0	0	0	0	0
6	3	3	3	3	3	2	1	1	0	0	0	0	0	0	0
5	2	3	3	3	2	2	1	0	0	0	0	0	0	0	0
4	2	2	2	2	2	2	1	0	0	0	0	0	0	0	0
3	2	2	2	2	2	1	1	0	0	0	0	0	0	0	0
2	2	2	2	2	2	1	1	0	0	0	0	0	0	0	0
1	1	2	2	2	1	1	0	0	0	0	0	0	0	0	0

AZIMUTH ANGLE -70. DEGREES

MAX SLOPE(DEG)	35.	33.	32.	32.	32.
MIN RANGE(M)	1.0	1.1	1.3	1.5	1.6
MAX RANGE(M)	1.2	1.4	1.5	1.8	1.8

MIN SLOPE(DEG)	26.	27.	26.	26.	
MIN RANGE(M)	0.9	1.1	1.2	1.4	
MAX RANGE(M)	1.5	1.6	1.9	1.9	

AZIMUTH ANGLE -60. DEGREES

MAX SLOPE(DEG)	39.	32.	32.	33.	33.
MIN RANGE(M)	1.1	1.2	1.3	1.5	1.7
MAX RANGE(M)	1.3	1.5	1.6	1.9	1.9

MIN SLOPE(DEG)	27.	27.	27.	27.	
MIN RANGE(M)	1.0	1.1	1.3	1.5	
MAX RANGE(M)	1.5	1.7	2.0	2.0	

AZIMUTH ANGLE -50. DEGREES

MAX SLOPE(DEG)	39.	38.	32.	32.	45.
MIN RANGE(M)	1.1	1.2	1.3	1.5	1.7
MAX RANGE(M)	1.3	1.4	1.6	1.6	1.8

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FIGURE 36

25x30 System, 30° slope; example of inconsistent estimates

A technique that will yield better results is to filter data from several scans. Table 2 shows maximum and minimum slope estimates obtained over six consecutive scans made by a 32x40 system as the vehicle approached a 30° slope. Along with each estimate is the location relative to the vehicle of the terrain associated with that estimate. In Table 3, the estimates are regrouped by location relative to the planet. Note that there are several slope estimates at each location. Each maximum slope estimate always overestimates the slope while each minimum always underestimates. Clearly, the best estimates are the least maxima and the greatest minima for each location. These estimates have been selected and placed in Table 4. These "filtered" estimates are a much more accurate representation of the terrain than any set of estimates from a single scan.

The benefits obtained from this technique must be weighed against the computational effort required for implementation. The coordinate transformation of the estimate locations from vehicle to planet frame is easy with a straight trajectory as in this example but is much more complicated otherwise. Furthermore, in this example the estimate locations were given as points. In reality, the estimates are taken over finite ranges of the terrain and often the ranges from consecutive estimates will overlap. Finally, in the example above, only data from the center azimuth are considered since those scans overlap when the vehicle is on a straight trajectory. The data obtained from off center azimuths do not overlap as much as in the 0° case. A more sophisticated algorithm would be needed to deal with this. Even with a complex algorithm, the best results will be obtained in the center of scan. The implications are that the resulting system will have better central visiion than peripheral vision. Actually,

TABLE 2

32x40 system, 30° slope
Maximum, minimum slope estimates and corresponding range estimates

Vehicle Location Planet Frame (meters)		Slop estimated (degrees) Range estimates, vehicle frame (meters)						
-1.8	Max	43	40	40	84	38		
	Range	1.9	2.1	7.2	2.4	2.6		
	Min	26	29	25	25			
	Range	1.8	2.0	2.1	2.3			
-1.5		47	44	33	32	40	83	
		1.6	1.8	1.8	2.0	2.2	2.5	
		28	27	25	27			
		1.6	1.7	1.8	1.9			
-1.2		33	32	[illegible]	34	34	34	41
		1.3	1.5	1.6	1.7	1.9	2.0	2.2
		27	27	26	26	27	26	
		1.3	1.4	1.5	1.6	1.8	2.0	
-1.0		38	30	32	37	36	31	36
		1.1	1.1	1.3	1.4	1.5	1.6	1.8
		28	28	27	27	28	27	
		1.0	1.1	1.2	1.3	1.5	1.5	
-0.7		34	33	36	35	32	33	
		1.0	1.1	1.2	1.3	1.4	1.5	
		30	28	30	29	28		
		1.0	1.0	1.1	1.2	1.3		
-0.4		33	33	31	32	31		
		0.9	1.0	1.1	1.2	1.3		
		29	28	28				
		0.9	1.0	1.0				

TABLE 3
32x40 system, 30° slope
Slope estimates from six consecutive
scans grouped by planet frame location

Terrain Location Planet frame (meters)	Maximum Slope Estimates (degrees)						Minimum Slope Estimates (degrees)					
0.0							26	28				
0.1	43	47	33	38	30		28	27	28			
0.2							29	27	27	27		
0.3	40	44	33	32	32	34	25	25	26	27	30	28
0.4	40	35	37	33			27	26	30			
0.5	32	34	36	36	33		25	28	27	29	29	
0.6	84	31	35	33			27	28	28	28		
0.7	40	34	32	31								
0.8	38	34	36	33	32		26					
0.9	31											
1.0	83	41										

TABLE 4

32x40 system, 30° slope

Best slope estimates obtained from six consecutive scans

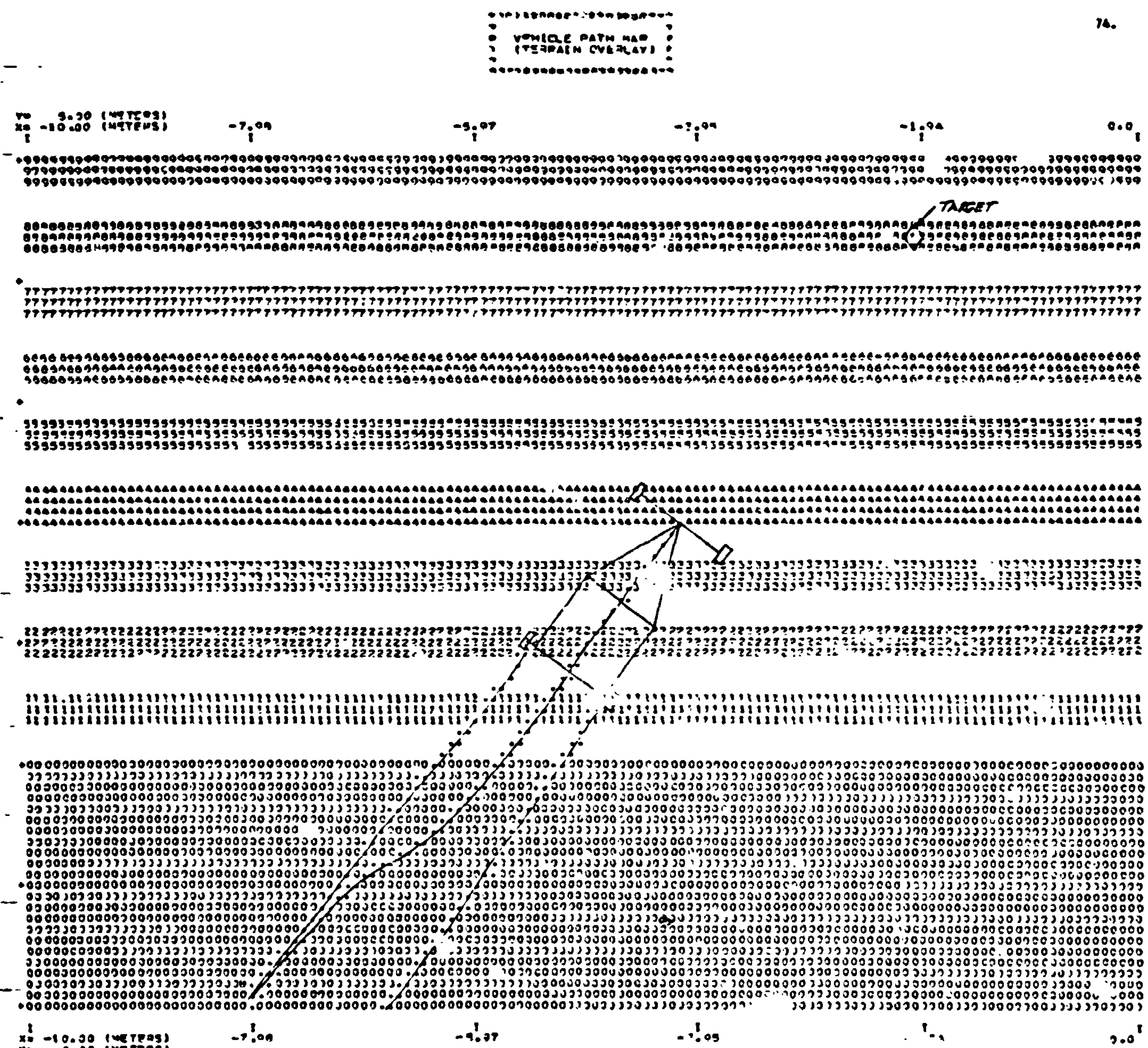
Terrain Location Planet Frame (meters)	Least Maximum Slope Estimate (degrees)	Greatest Minimum Slope Estimate (degrees)
0.6	-	28
0.1	30	28
0.2	-	29
0.3	32	30
0.4	33	30
0.5	32	29
0.6	31	28
0.7	31	-
0.8	32	26
0.9	31	-
1.0	41	-

this is not necessarily a problem at all since the human eye behaves in the same way.

All of the drawbacks listed above can be overcome at the cost of increased computer time. Only further study will tell whether or not the additional computing is justified. In theory, the idea has merit because it makes use of all of the data available. With a system as crude as the one studied here, discarding even a small amount of data can substantially degrade results. The technique has the further advantage that the estimates are done recursively. This greatly reduces the effort required as opposed to storing all of the data in a constantly updated map. Much more storage and calculating time are required with the map method.

Returning to the comparison of the three simulations on 30° slopes, increased data density does provide better estimates. Better estimates result in more accurate distinctions between safe terrain and hazards and allow the vehicle to travel a more direct course towards its target. In the simulations, the trajectory followed for the 32x40 is steeper than with the 15x20, Figures 37 and 38. Furthermore, the trajectory for the 32x40 could have been steeper still if the vehicle had not been constrained to a heading of 40°. The performance of the 15x20 system is nonetheless, admirable. Slopes from -20° to +20° are negotiated with absolutely no problems. More severe slopes can also be handled but the vehicle must approach at an angle. The amount of uncertainty increases with increasing slopes so that steering commands become more erratic.

Another group of simulations places the vehicle on sinusoidal terrains of varying amplitude. The purpose is to test the ability to deal with a variety of constantly varying terrain situations. While the results



SYMBOL	0	1	2	3	4	5	6	7	8	9
RANGE OF ALTITUDES (METERS)	-0.09 TO 0.16	0.33 TO 0.51	0.68 TO 0.86	1.03 TO 1.21	1.38 TO 1.55	1.73 TO 1.90	2.08 TO 2.25	2.43 TO 2.60	2.78 TO 2.95	3.13 TO 3.30

0 .... INITIAL VEHICLE LOCATION

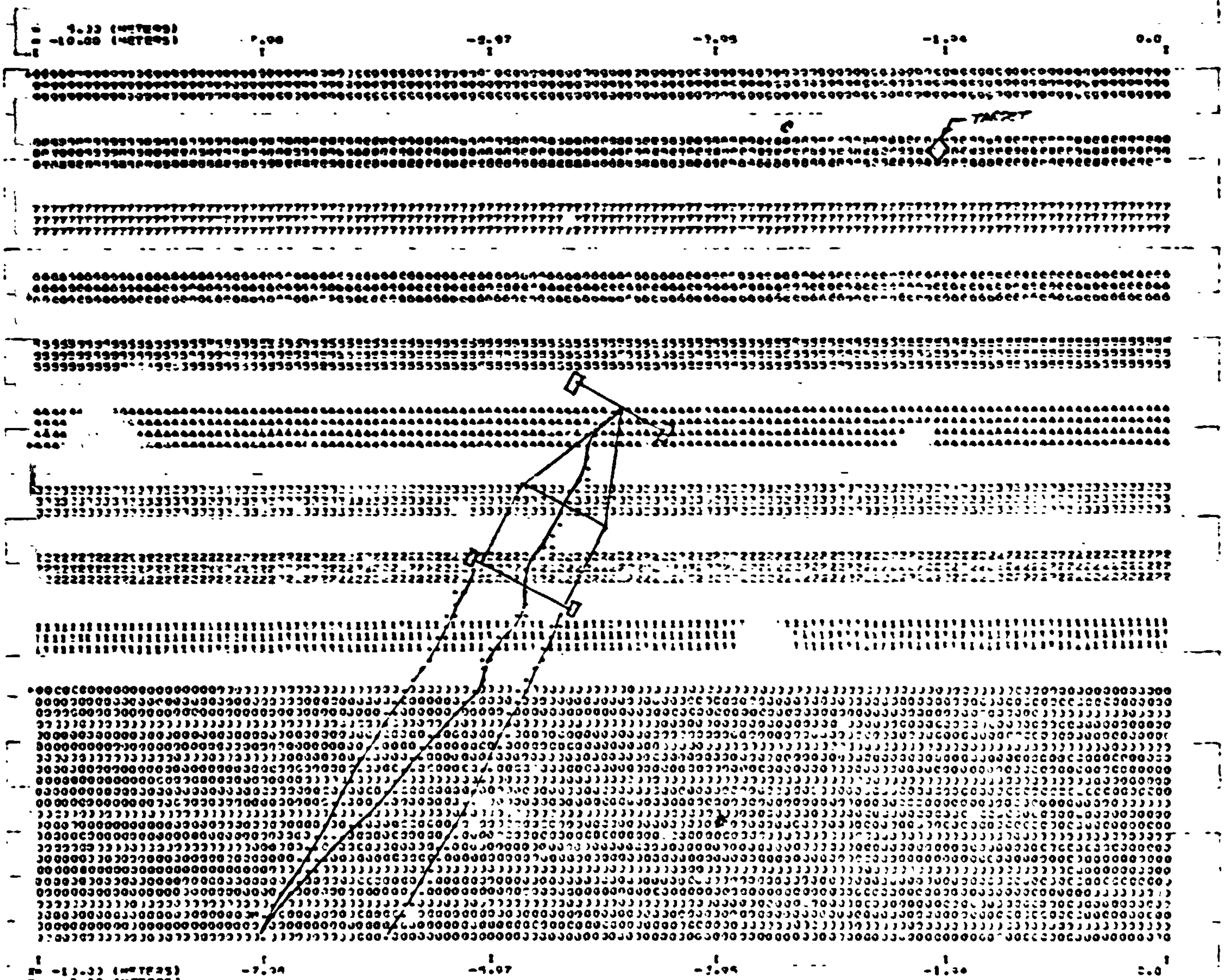
$ .... MID-RANGE SENSOR CORRECTION

. ... VEHICLE PATH

* .... TARGET LOCATION

FIGURE 37
Vehicle trajectory, 15x20 system
30° slope

VEHICLE PATH MAP
(TERRAIN OVERLAY)



SYMBOL	0	1	2	3	4	5	6	7	8	9
RANGE OF ALTITUDES (METERS)	-0.32 TO 0.18	0.3[illegible] TO 0.51	0.68 TO 0.88	1.03 TO 1.21	1.[illegible] TO 1.55	1.73 TO 1.90	2.08 TO 2.25	2.42 TO 2.60	2.79 TO [illegible]	3.1[illegible] TO 3.30

0 .... INITIAL VEHICLE LOCATION

S .... MID-RANGE SENSOR OPERATION

. ... VEHICLE PATH

\# .... TARGET LOCATION

FIGURE 38
Vehicle trajectory, 32x40 system
30° slope

look good, they are more difficult to interpret quantitatively than the previous simulations. This is primarily due to the fact that it is difficult to imagine what the vehicle sees during a scan under arbitrary pitch and roll conditions. Also, an error has been found in the simulation subroutine that adjusts the sensor attitude for vehicle roll. Subsequent simulations will be affected to some degree by this defect.

Three simulations are performed on a sine wave with 6.0 meter period and amplitudes of 0.25, 0.30, and 0.40 meters. These are chosen to duplicate simulations performed earlier to test the previous one, two, and three laser/detector systems.[4] In all cases the new 15x20 system performed as well or better than previous systems, as would be expected. The run for 0.25 meters amplitude poses no problem at all as the vehicle is able to travel a direct heading. The maximum computed slopes are ±22° which compares to true maximum local slopes of ±14.5°.

The 0.3 meter amplitude case reveals an additional problem. The primary source of trouble is a small field of view. As the vehicle scans down from a crest into a trough, the closest laser shots are not seen because the terrain falls below the detector field, Figure 39. The algorithm is set to identify four or more consecutive missed returns as an obstacle. It is total lack of data, not poor data, that causes the vehicle to turn. Laser shots are also missed at the far end when terrain rises above the detector field. This occurs especially when the vehicle is pitched downward.

The problems with missed returns become more pronounced in the 0.4 meter case. In addition to laser shots hitting outside of the detector field, the terrain falls off so quickly nor (maximum of ±22.5°) that some laser shots aimed into troughs are blocked by the slope, Figure 40. While the number of missed returns due to this is not sufficient to be hazardous, greater amplitudes will no doubt be impassable as this effect will worsen.

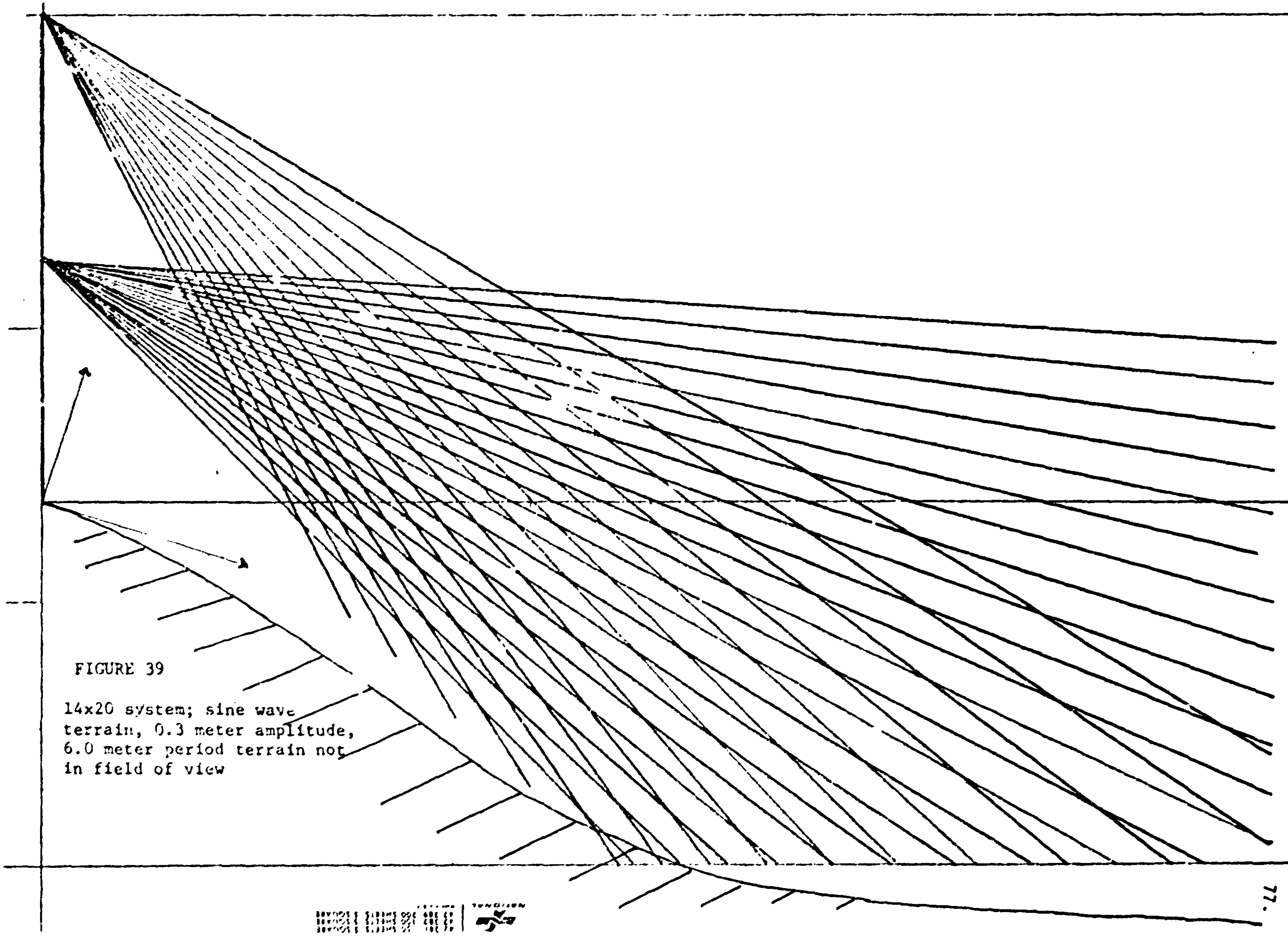


FIGURE 39

14x20 system; sine wave terrain, 0.3 meter amplitude, 6.0 meter period terrain not in field of view

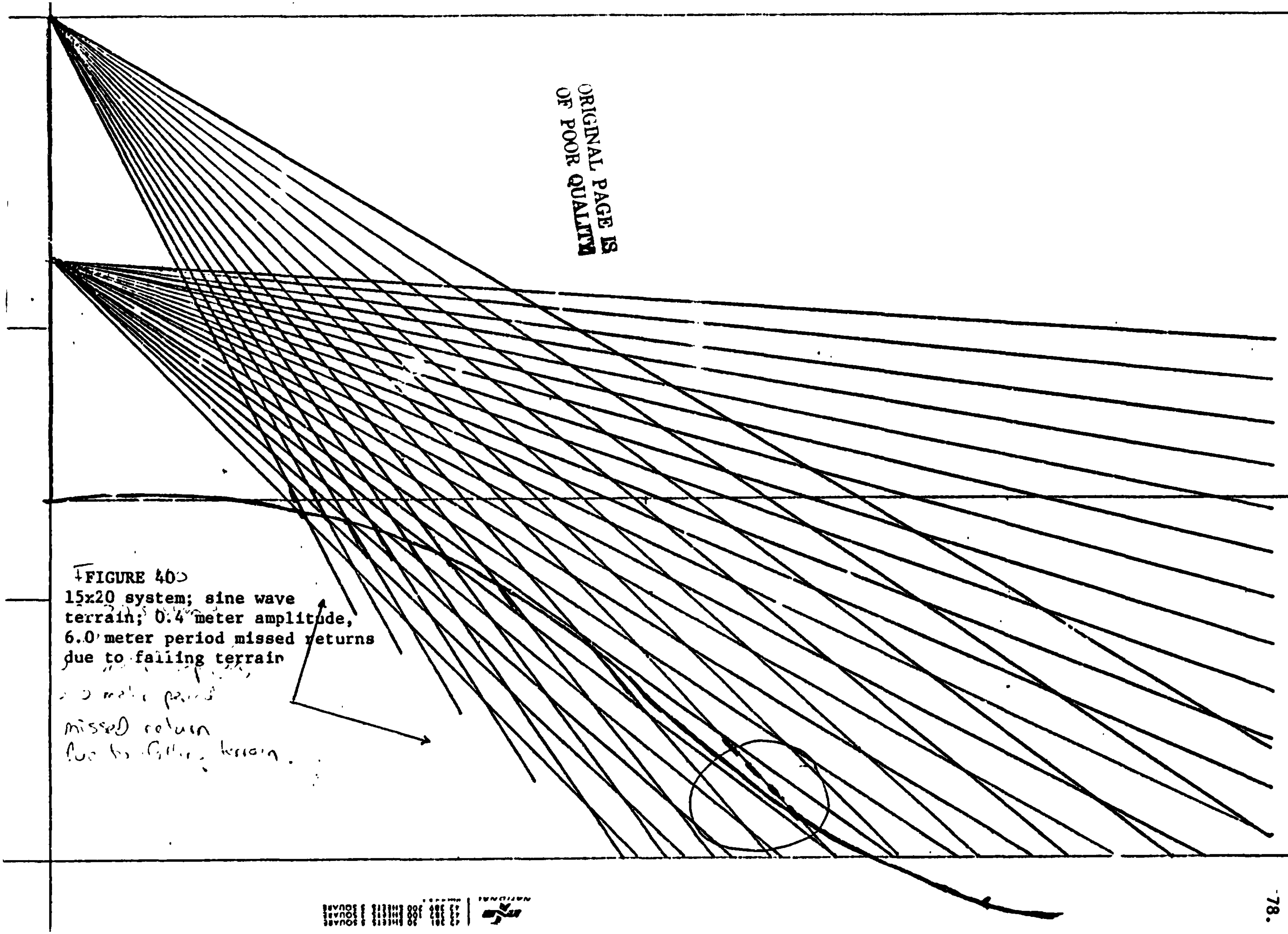


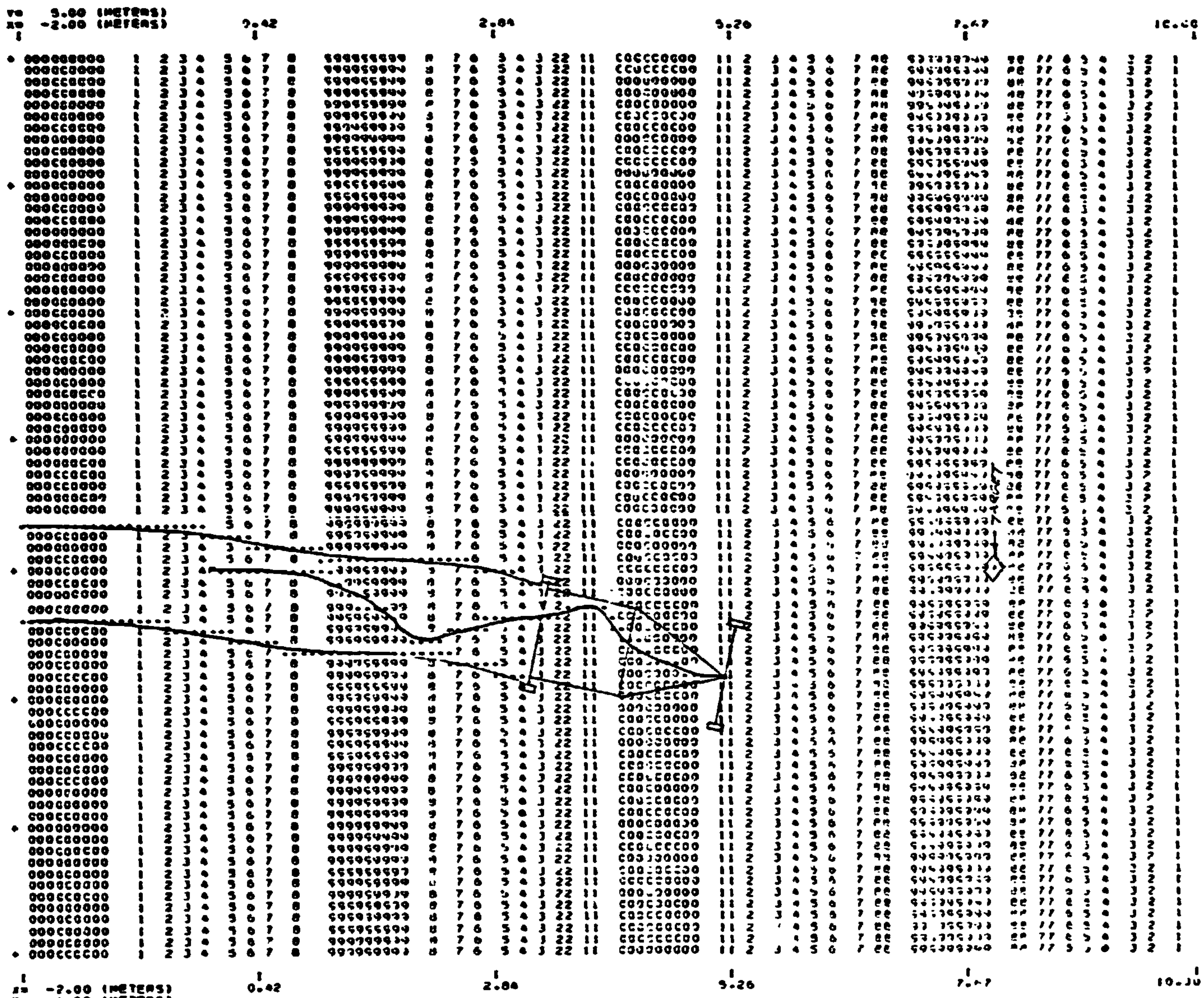
FIGURE 40
15x20 system; sine wave terrain; 0.4 meter amplitude, 6.0 meter period missed returns due to falling terrain

Furthermore, the maximum slope estimates at close range are approaching 30° and are just barely acceptable. In spite of this, both the 0.3 and 0.4 meter cases are traversed with nearly straight trajectories, Figure 41. Since the trajectories are almost straight, the vehicle roll is is small and the error in correcting the scanner altitude is, likewise, small. The simulation results are, therefore, reliable.

The last simulation tests the 15x30 system on a field of shallow boulders and craters, Figure 42. Most of them are small enough that they can be safely traversed. They are merely added t[illegible] terrain uneven and cause variable pitch and roll situati[illegible] hazardous boulders and craters are interspersed and they [illegible] be detected from among the other features.

The vehicle performs well and is able to traverse the boulder/crater field without mishap. On the first two scans hazards are detected. This comes as a surprise since the terrain was intended to be safe at that point. What is seen is a 0.15 meter deep crater adjacent to a 0.15 meter boulder. The features are safe when considered separately. When put together, though, the combination yields an average slope of 20° over a 0.25 meter rise with a maximum instantaneous slope of 37°. This compares to predicted slopes of 34°-36°. It is possible that the algorithm made the correct, though unexpected, decision. A sharp turn follows and the vehicle makes a successful attempt to enter the field at another point. It proceeds on a direct course toward the target passing alongside a 0.25 meter deep crater. Contrary to expectations, the crater is not considered hazardous by the vehicle. Again there is a problem as to how the feature should be interpreted. With a depth of 0.25 meters, a maximum local slope of 48°, and an average slope of 18.5" from edge to center, it is not clear

VEHICLE PATH MAP
(TERRAIN OVERLAY)



SYMBOL	0	1	2	3	4	5	6	7	8	9
RANGE OF ALTITUDES (METERS)	-0.40 TO -0.36	-0.32 TO -0.28	-0.23 TO -0.1[illegible]	-0.15 TO -0.11	-0.0[illegible] TO -0.02	0.02 TO 0.06	0.11 TO 0.15	0.19 TO 0.23	0.[illegible] TO 0.32	0.3[illegible] TO 0.40

H .... INITIAL VEHICLE LOCATION

S .... MID-RANGE SENSOR OPERATION

. ... VEHICLE PATH

◆ .... TARGET LOCATION

FIGURE 41
Vehicle trajectory
15x20 system; sine wave terrain,
0.4 meter amplitude
6.0 meter period

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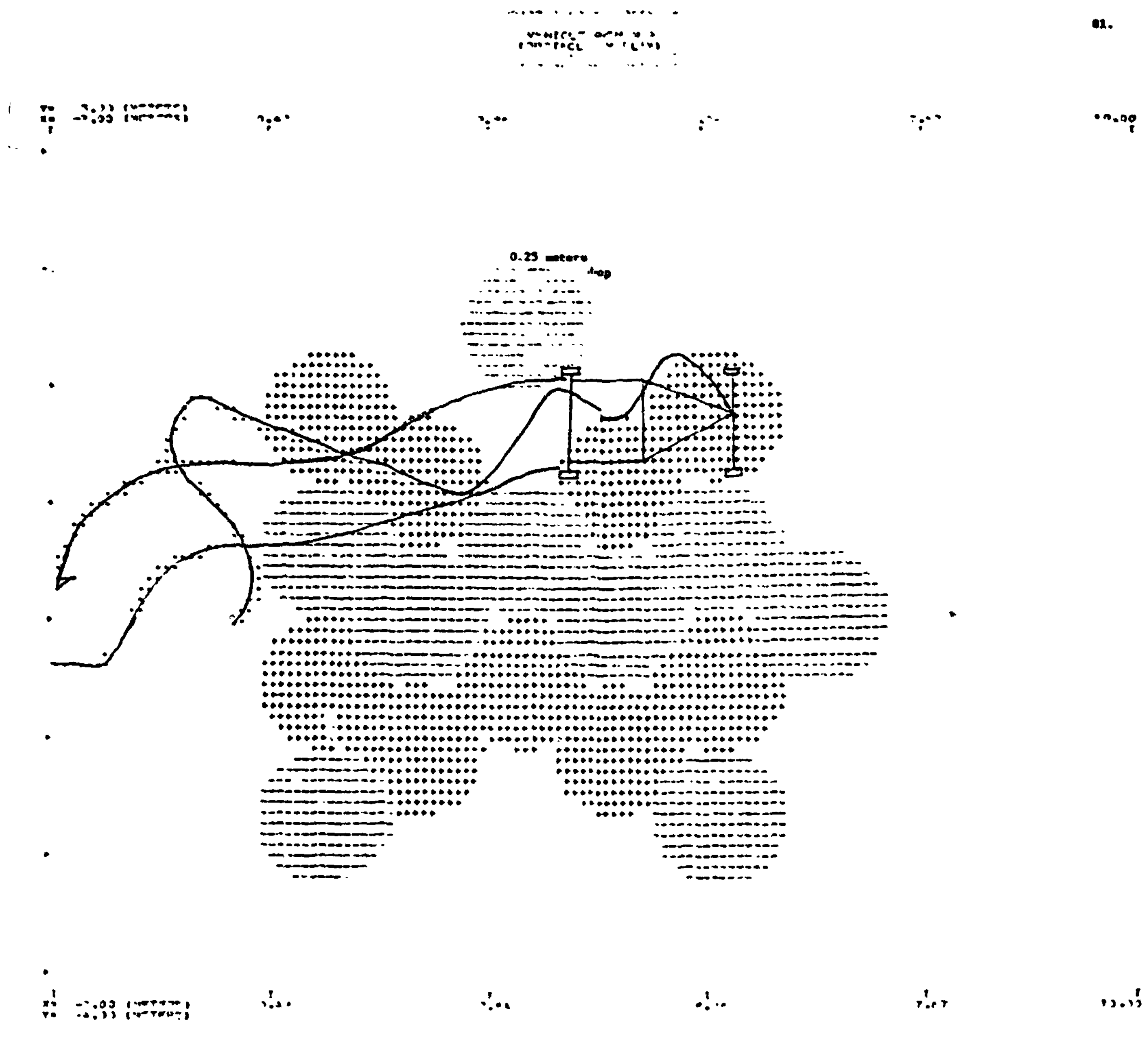


INITIAL VEHICLE LOCATION

TARGET LOCATION

FIGURE 42

Vehicle trajectory 15x20 system, Boulder, Crater field whether or not the crater is hazardous by the given algorithm. This is especially true since a local slope cannot be determined by the scanner. The decision is made more difficult considering the vehicle's distance from the crater and its pitch and roll situation. The fact that the vehicle has some roll casts some doubt as to the validity of the results. Interestingly, the crater is definitely not hazardous because of its small size compared to the vehicle dimensions. If the vehicle were to pass through the crater, it would experience a maximum pitch of 7° and a maximum roll of 9.5°. Of course the present algorithm is not expected to take these considerations into account. A more sophisticated algorithm is required that estimates the vehicle's expected pitch and roll instead of or in addition to the terrain slope.

The question as to whether or not the 15x20 system considered the 0.25 meter crater hazardous has not been answered yet. The only way to get the answer is to repeat the simulation after correcting the program for the roll adjustment error. What this simulation does demonstrate, though, is that the question of defining a hazard is by no means trivial. More work must be done to extend the simple rules developed here.

In all of the simulations, the 15x20 system with the hazard detection algorithm is able to steer clear of all obstacles. Unfortunately, some safe terrain is also avoided. This is necessary since all ambiguous cases must be treated with caution. It was seen that one of the best ways of improving the performance is to increase data density and accuracy by going to higher order scanning systems. The number of bad estimates is reduced thereby minimizing the variation of computed slopes. Just as important is the accuracy of the data interpreter. The algorithm developed is quite reliable since it makes use of all of the data available in a scan and attempts to account for all possibilities. However, the decisions made are based on some oversimplified assumptions and techniques and could stand some improvement. It must be stressed that this is not disastrous since the assumptions lend to make the algorithm more conservative in decision making. While the algorithm does use all of the data taken in a scan, it ignores data taken from previous, overlapping scans. No doubt the additional information would be helpful but the tradeoff is a much more time consuming program.

Even with the difficulties mentioned above, there is absolute confidence in the slope estimates. Not once did the true terrain slope lie outside the bounds predicted by the maximum and minimum slope calculations. Sometimes this is hard to ascertain since the estimates are only averages taken over a finite range interval in which the terrain slope is varying. Furthermore, the maximum slope estimates are usually computed over a shorter range than the minimum slopes. As a result, it is sometimes difficult to attach physical meaning to the estimated range of slopes when the upper and lower bounds do not represent the same terrain, Figure 43. The estimates are still no less correct in spite of this.

Another potential problem demonstrated by the simulations is inadequate field of view. With a small field of view, there will be times when absolutely no information is received about a section of terrain. This is particularly dangerous when the area in question is very close to the vehicle. The only decision a cautious vehicle can make when no information is given is to choose another path. This is an unnecessary hindrance to the vehicle. The additional lasers and detectors needed to cover the entire field of view would be a worthwhile modification. Assuming the

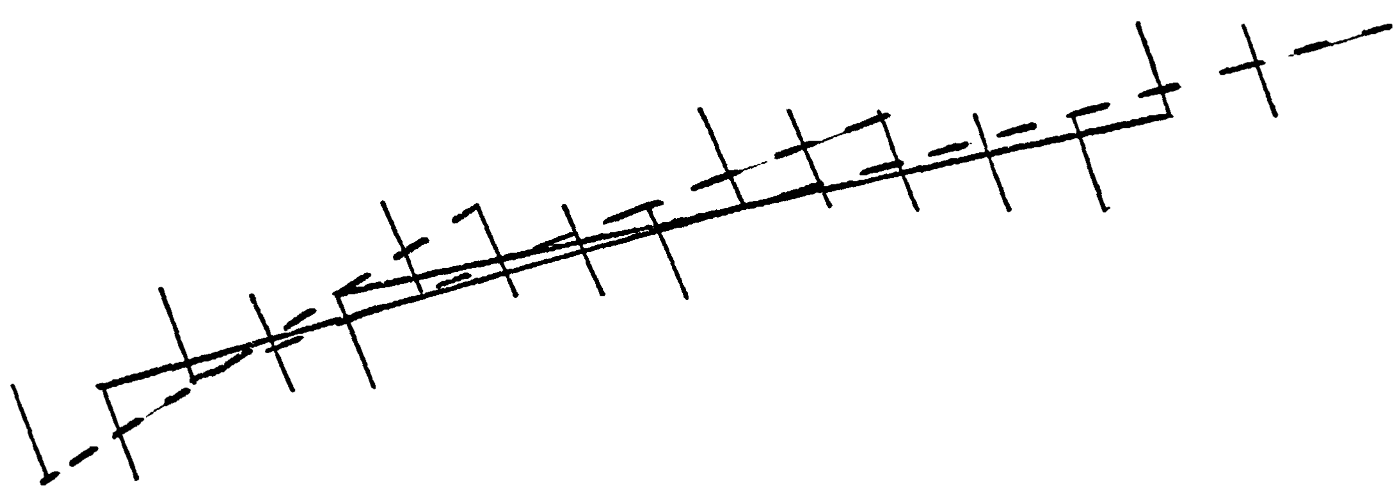
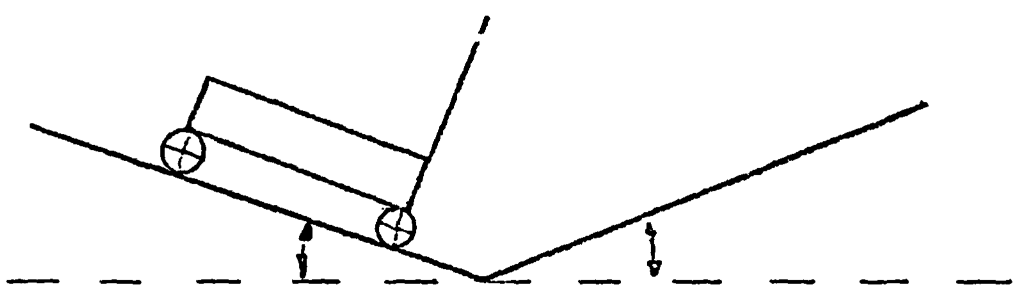


FIGURE 43

Example of calculated slopes demonstrating difficulty in attaching physical significance to estimates vehicle will never have a pitch in excess of ±30°, a 60° field of view is recommended. At 2° per detector, this requires an additional ten detectors. Given a fixed number of detectors, the field of view problem is a tradeoff between adequate peripheral vision and accurate center vision. Expanding the field of view without adding additional detectors degrades the data overall. One solution might be to concentrate most of the laser shots and detectors directly in front of the vehicle. This would insure that one very accurate scan can be obtained. To deal with the peripheral vision problem, additional lasers and detectors with greater spacing could cover the fringe areas. These would be used mainly to signal a major shift in the terrain. If the terrain rises or falls greatly or if the vehicle is pitched, the scanner can be rotated so that it again focuses on the ground immediately in front of the vehicle. Naturally, this would require a degree of sophistication that has not yet been reached with the R.P.I. rover. However, the idea is by no means unrealistic.

There is one great limitation with the hazard detection algorithm that has not ever been considered in this paper. This data processor was designed to interpret data in a single azimuthal scan. Unfortunately, gradients occur in all directions and these are totally overlooked. It is entirely possible to have safe slopes in the inpath direction but hazardous slopes in the crosspath sense, Figure 44. This happens, for instance, when the vehicle travels across the face of a slope. One way of dealing with the problem would be to try to estimate crosspath information from inpath slopes. As an example, suppose a 20° slope is indicated one azimuth while an adjacent one is estimated at -20°. It is apparent that while both paths are safe in the inpath sense, a sharp change occurs in the crosspath direction. This technique, though, is qualitative at best and gives much more

Vehicle Attitude Problem
side view



Crosspath Hazard Problem
front view

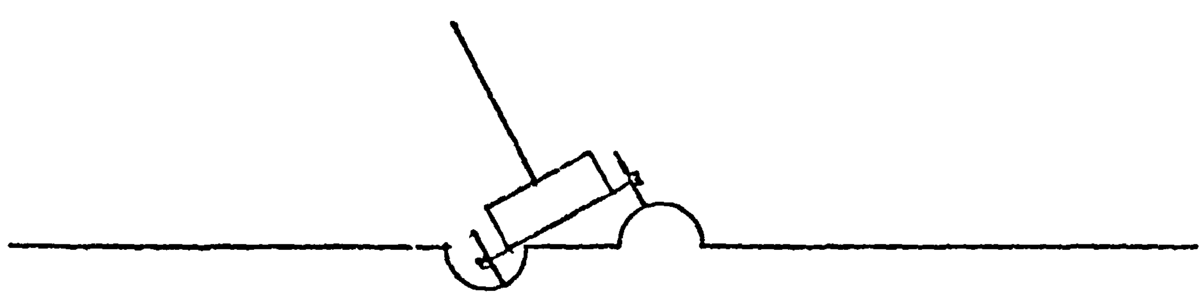


FIGURE 44
Vehicle Attitude and Cross[illegible] Considerations

emphasis to the inpath interpretation. There is no reason to believe that the inpath slope is any more important than the crosspath slope. To give equal treatment to the crosspath case, the algorithm used for the inpath data can also be applied to data perpendicular to the path. The main problem with this solution is that except for very close ranges, the data density in the crosspath sense is less than in the azimuths. Terrain interpretation would be difficult. This can be remedied by taking the azimuth shots at increments smaller than 10°. To maintain the same 150° sweep, this requires more azimuths, more data, and more processing time. Another alternative is to make the azimuth shots closer together but to use the same number. This concentrates them in a much smaller area. The center vision is again improved at the expense of peripheral vision. It would appear that the tradeoff is worth it since the terrain immediately in front of the vehicle is of the greatest concern. If a sharp turn is required, a scan in the new direction can be made before any action is taken.

The hazard detection algorithm presented here does have some weak areas that require further study. Most important among these are the need for crosspath slope information and a more refined conception of what an obstacle is. The main purpose of this investigation, however, was to determine whether or not a multi-laser/detector triangulation hazard sensing system is feasible. This has been accomplished. Despite resolution problems, reasonably accurate terrain characterizations have been made using the R.P.I. system. More importantly, reliable bounds have been placed on the terrain estimates. It is for this reason that the R.P.I. rover never found itself in a dangerous situation and this is an important consideration when planning a Mars mission. Without the hardware constraints limiting the R.P.I. system, increased resolution and performance are possible with a triangulation sensor. Increased laser density increases the quantity of data and finer individual detector fields improve the accuracy. The amount of information available from the data, however, is a function of the spacing of both the lasers and detectors. Furthermore, it is, in theory, possible to extract the maximum amount of information available from a given sensor and to easily construct an accurate envelope enclosing the terrain. Even with the limited data and large uncertainties characteristic of the R.P.I. system a short range multi-laser/detector triangulation sensor, by virtue of its speed, can compete with larger range sensors. This work serves as a basis for further investigation that should further strengthen the case for the short range sensor.

VIII. CONCLUSIONS

Computer simulations have shown that a 15 laser, 20 detector triangulation sensor can be used for hazard detection on an autonomous roving vehicle. An algorithm has been developed that, regardless of the type of terrain, calculates terrain slope estimates allowing the vehicle to locate and avoid obstacles. Because of ambiguity inherent in the system maximum and minimum slope estimates are computed to account for all terrain possibilities. The price to be paid is that if the range of slopes is large, a conservatively biased vehicle declares some safe paths as hazardous.

It is possible to improve perception by increasing laser density. While this does not improve accuracy, the extra laser pulses increase the amount of data. Making detector fields smaller increases data accuracy without adding to the total number of data points. Computer simulations have shown that the combined effect of decreased laser spacing and reduced detector fields is to reduce the ambiguity in the system and increase the number of safe paths available.

It is evident from simulations that a 40° overall field of view is insufficient to detect all safe terrains. Theoretical considerations suggest a 60° field would substantially improve the terrain interpretations.

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APPENDIX A -- CODE LISTINGS

A. Subroutine DIAGNL - This subroutine diagonalizes the laser/sensor returns.

B. Subroutine MODEL 2 - This subroutine processes the laser/sensor returns in accordance with the terrain modeling rules

```
      SUBROUTINE DIAGNL
      COMMON/SENSR/BEMRNG,ASMUTH,LANGLE,RTN,KOUNT,ISCAN
      COMMON/SENX/HITLAS,HITSEN,NUMLAS,NUMSEN,NUMAZ,INTDAT,
     &  NMDTPR,LASAGL,SENGLE,SCON,DATA,DIAG,POS
      INTEGER DIAG(50,50),RTN(50)
      INTEGER*2 DATA(50,50)
      REAL ASMUTH(50),POS(50,51,2),LASAGL(50),SENGLE(50)
      REAL BEMRNG(50),LANGLE(50)
      DO 100 J=1,NUMAZ
      DO 100 I=1,NUMLAS
      DIAG(J,I)=DATA(J,I)-I
100   IF(DATA(J,I).EQ.0) DIAG(J,I)=1000
      WRITE(6,200)
200   FORMAT('1',10X,'DIAGONALIZED RETURN')
      WRITE(6,300) (J,J=1,NUMAZ)
300   FORMAT('0','AZIMUTH',3X,50(1X,I2,1X))
      WRITE(6,400)
400   FORMAT('0','LASER')
      DO 500 I=1,NUMLAS
      K=NUMLAS-I+1
500   WRITE(6,600) K,(DIAG(J,K),J=1,NUMAZ)
600   FORMAT(' ',3X,I2,5X,50(I3,1X))
      RETURN
      END
```

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      SUBROUTINE MODEL2
      COMMON/CHOOSE/NMMOD,NMSEN,NMPSA,NMTRN,INTVDB,INTSEN,
     & INTMOD,INTPSA,INTTRN,INTGYR
      COMMON/TIEUP/THETNU,ALPHA,SLPIN,SLPCRS,SLPCHS,TALLOW
      COMMON/DYNMIC/DWNMAX,UPMAX,VEHLEN,VEHWID,CRSMAX,VELMAX,
     & DT,TURN1,STRMAX
      COMMON/SENSR/BEMRNG,ASMUTH,LANGLE,RTN,KOUNT,ISCAN
      COMMON/SLOPE/SLPMAX,SLPMIN,ISTOP1,ISTOP2
      COMMON/DETECT/SENTIM,SCNTIM,TIMSTP,SENSTP,SENHI,SENLIM,
     & SENLEN,SENWID,NUMBER,IJK
      COMMON/SENX/HITLAS,HITSEN,NUMLAS,NUMSEN,NUMAZ,INTDAT,NMDTPR,
     & LASAGL,SENGLE,SCON,DATA,DIAG,POS
      REAL RANGE(50),SLPMAX(50,50,3),SLPMIN(50,50,3),AZMUTH(50),
     & ASMUTH(50),POS(50,51,2),LASAGL(50),SENGLE(50)
      REAL BEMRNG(50),LANGLE(50)
      INTEGER HAZARD(50),DELTA,JUMP(50,2),SEN1,SEN2,SEN3,SEN4
      INTEGER RTN(50),DIAG(50,50)
      INTEGER*2 DATA(50,50)
      IF(IJK.GT.0) GO TO 70
      READ(5,30) MXMISS,ZMAX,RNGMIN
30    FORMAT(I2,8X,2F10.5)
      CONVRT=180./3.14159
      DO 50 I=1,NUMAZ
50    AZMUTH(I)=ASMUTH(I)*CONVRT
      RETURN
70    CALL DIAGNL
C     DO ONE LOOP PER AZIMUTH
      DO 4000 J=1,NUMAZ
      I=1
C     CHECK FIRST RETURNSFOR MISSING DATA
C    MXMISS IS MAXIMUM NUMBER OF MISSES ALLOWED. IF THIS IS EXCEEDED
C          STORE INFORMATION TO BE PRINTED AND GO TO NEXT AZIMUTH
 100  IF(DIAG(J,I).NE.1000) GO TO 300
      IF(I.EQ.MXMISS) GO TO 200
      I=I+1
      GO TO 100
 200  RANGE(J)=1.
      HAZARD(J)=2
      GO TO 4000
C     ISTRT INDICATES FIRST LASER MAKING HIT
 300  ISTRT=I
C     LOOK FOR MISSING RETURNS
 400  IF(I.EQ.NUMLAS) GO TO 800
      I=I+1
      IF(DIAG(J,I).NE.1000) GO TO 400
C     IMISS1 - FIRST LASER WITH MISSING RETURN
      IMISS1=I
C     MAX. NO. OF MISSES EXCEEDED?
 500  IF(I-IMISS1.GE.MXMISS) GO TO 700
      I=I+1
C     LOOK FOR NEXT HIT
      IF(I.GT.NUMLAS) GO TO 900
      IF(DIAG(J,I).EQ.1000) GO TO 500
C     IMISS2 - LAST LASER WITH MISSED RETURN
      IMISS2=I-1
C     COMPARE DIAGONALIZED RETURNS BEFORE AND AFTER MISSES;
C     INSERT LOWER DIAGONALIZED RETURN AND CORRESPONDING SENSOR
C     THAT WOULD HAVE SEEN LASER AT ALL MISSES
      DELTA=MIN0(DIAG(J,I),DIAG(J,IMISS1-1))
      DO 600 K=IMISS1,IMISS2
```

```
      DIAG(J,K)=DELTA
      DATA(J,K)=K+DELTA
 600  CONTINUE
      GO TO 400
C     IF TOO MANY MISSES, STORE RANGE OF LAST HIT.
C     HAZARD INDICATES TYPE OF OBSTACIE AND IS USED LATER.
 700  IHIT=IMISS1-1
      ISAW=DATA(J,IHIT)
      RANGE(J)=POS(IHIT,ISAW,2)
      HAZARD(J)=2
      GO TO 4000
 800  ISTOP=NUMLAS
      GO TO 1000
C     REMEMBER LASER THAT MADE LAST HIT
 900  ISTOP=IMISS1-1
 1000 IF(IFIX(SLPIN/(CONVRT*20.)))1100,1500,1300
C     IF PITCH<-20 CHECK FOR NEG.OBSTACLES
C     IF PITCH>20 CHECK FOR POS. OBSTACLES
 1100 DO 1200 K=ISTRT,ISTOP
      IF(DIAG(J,K).GE.DIAG(J,ISTRT))GO TO 1200
      ISAW=DATA(J,K)
      RANGE(J)=POS(K,ISAW,2)
      HAZARD(J)=3
      GO TO 4000
 1200 CONTINUE
      GO TO 1500
 1300 DO 1400 K=ISTRT,ISTOP
      IF(DIAG(J,K).LE.DIAG(J,ISTRT))  GO TO 1400
      ISAW=DATA(J,K)
      RANGE(J)=POS(K,ISAW,2)
      HAZARD(J)=4
      GO TO 4000
 1400 CONTINUE
C     ICOUNT - COUNTS NUMBER OF DIAG. JUMPS
 1500 ICOUNT=0
C     COMPUTE LOCATION & SIZE OF ALL DIAGONAL JUMPS AND STORE
C     IN JUMP
C     JUMP(N,1) - LASER BEFORE N-TH JUMP
C     JUMP(N,2) - SIZE OF N-TH JUMP
      ISTOP1=ISTOP-1
      IF(ISTOP1.EQ.0)GOTO 1610
      DO 1600 I=ISTRT,ISTOP1
      DELTA=DIAG(J,I+1)-DIAG(J,I)
      IF(DELTA.EQ.0)  GO TO 1600
      ICOUNT=ICOUNT+1
      JUMP(ICOUNT,1)=I
      JUMP(ICOUNT,2)=DELTA
 1600 CONTINUE
C     CHECK FO NO DIAG. JUMPS
 1610 IF(ICOUNT.NE.0)GOTO 1650
      HAZARD(J)=1
      GO TO 4000
C     JCOUNT COUNTS NO. OF SLOPES CALCULATED & CHECK FOR LAST JUMP
 1650 K=1
      JCOUNT=0
 1700 IF(K.GT.ICOUNT)  GO TO 2200
      INCR=0
C      N INDICATES SIGN OR JUMP, IF JUMP<0 ,N=-1
      N=1
      LAS1=JUMP(K,1)
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      SEN1=IFIX(DATA(J,LAS1)+.5-N/2.)
      Z1=POS(LAS1,SEN1,1)
      IF(N*JUMP(K,2).GT.1) GO TO 1900
 1800 INCR=INCR+1
C     LOOK FOR DIAG.JUMP=2,IF JUMP CHANGES DIRECTION,STOP
      IF(K+INCR.GT.ICOUNT) GO TO 2200
      IF(N*JUMP(K+INCR,2).LT.0) GO TO 2000
 1900 LAS2=JUMP(K+INCR,1)+1
      SEN2=IFIX(DATA(J,LAS2)+.5+N/2.)
      Z2=POS(LAS2,SEN2,1)
      DELZ=Z2-Z1
      IF(ABS(DELZ).GE.ZMAX) GO TO 2100
      GO TO 1800
 2000 K=K+INCR
      GO TO 1700
C     COMPUTE MAXIMUM SLOPE
 2100 IF(LAS2-LAS1.LE.2) GO TO 2150
      LAS3=LAS1+1
      LAS4=LAS2-1
      SEN3=IFIX(DATA(J,LAS3)+.5-N/2.)
      SEN4=IFIX(DATA(J,LAS4)+.5+N/2.)
      Z3=POS(LAS3,SEN3,1)
      Z4=POS(LAS4,SEN4,1)
      R3=POS(LAS3,SEN3,2)
      R4=POS(LAS4,SEN4,2)
      DELZ=Z4-Z3
      GO TO 2170
 2150 R3=POS(LAS1,SEN1,2)
      R4=POS(LAS2,SEN2,2)
 2170 DELR=R4-R3
      JCOUNT=JCOUNT+1
      SLPMAX(J,JCOUNT,1)=ATAN2(DELZ,DELR)
      SLPMAX(J,JCOUNT,2)=R3
      SLPMAX(J,JCOUNT,3)=R4
      K=K+1
      GO TO 1700
C     STORE NUMBER OF SLOPES CALCULATED
 2200 ISTOP1=JCOUNT
      IF(ISTOP1.NE.0) GO TO 2250
      HAZARD(J)=8
      GO TO 4000
 2250 K=1
      JCOUNT=0
 2300 IF(K.GT.ICOUNT) GO TO 2800
      INCR=0
      N=1
      IF(JUMP(K,2).LT.0) N=-1
      LAS1=JUMP(K,1)
      SEN1=IFIX(DATA(J,LAS1)+.5+N/2.)
      Z1=POS(LAS1,SEN1,1)
      IF(N*JUMP(K,2).GT.1) GO TO 2500
 2400 INCR=INCR+1
      IF(K+INCR.GT.ICOUNT) GO TO 2800
      IF(N*JUMP(K+INCR,2).LT.0)GO TO 2600
 2500 LAS2=JUMP(K+INCR,1)+1
      SEN2=IFIX(DATA(J,LAS2)+.5-N/2.)
      Z2=POS(LAS2,SEN2,1)
      DELZ=Z2-Z1
      IF(ABS(DELZ).GT.ZMAX)GO TO 2700
      GO TO 2400
```

```
 2600    K=K+INCR
         GO TO 2300
 2700    R1=POS(LAS1,SEN1,2)
         R2=POS(LAS2,SEN2,2)
         DELR=R2-R1
         JCOUNT=JCOUNT+1
         SLPMIN(J,JCOUNT,1)=ATAN2(DELZ,DELR)
         SLPMIN(J,JCOUNT,2)=R1
         SLPMIN(J,JCOUNT,3)=R2
         K=K+1
         GO TO 2300
 2800    ISTOP2=JCOUNT
C        ADJUST SLOPES FOR VEHICLE ATTITUDE
         CALL PITCH(J)
C        SEARCH FOR OBSTACLES
C        FIRST CHECK SLPMAX FOR CLOSEST SLOPE>CRITICAL VALUE
         DO 2900 I=1,ISTOP1
         IF(SLPMAX(J,I,1).LT.UPMAX.AND.SLPMAX(J,I,1).GT.DWNMAX) GO TO 2900
         IF(SLPMAX(J,I,2).GT.RNGMIN) GO TO 3000
         RANGE(J)=SLPMAX(J,I,2)
         HAZARD(J)=5
         GO TO3200
 2900    CONTINUE
         HAZARD(J)=8
         GO TO 3200
 3000    IF(ISTOP2.EQ.0) GO TO 3100
         DO 3100 I=1,ISTOP2
         IF(SLPMIN(J,I,1).LT.UPMAX.AND.SLPMIN(J,I,1).GT.DWNMAX) GO TO 3100
         RANGE(J)=SLPMIN(J,I,2)
         HAZARD(J)=6
         GO TO 3200
 3100    CONTINUE
         HAZARD(J)=7
 3200    IF(INTMOD.NE.1) GO TO 4000
         WRITE(6,3300) AZMUTH(J)
 3300    FORMAT('-','AZIMUTH ANGLE ',F4.0,' DEGREES')
        IF(ISTOP1.LT.1) GO TO 3620
        DO 3320 I=1,ISTOP1
 3320   SLPMAX(J,I,1)=SLPMAX(J,I,1)*CONVRT
         WRITE(6,3400) (SLPMAX(J,I,1),I=1,ISTOP1)
 3400    FORMAT('0','MAX SLOPE(DEG) ',50(2X,F4.0))
         WRITE(6,3500) (SLPMAX(J,I,2),I=1,ISTOP1)
 3500    FORMAT(' ','MIN RANGE(M) ',2X,50(2X,F5.1))
         WRITE(6,3600) (SLPMAX(J,I,3),I=1,ISTOP1)
 3600    FORMAT(' ','MAX RANGE(M) ',2X,50(2X,F5.1))
 3620   IF(ISTOP2.LT.1) GO TO 4000
        DO 3640 I=1,ISTOP2
 3640   SLPMIN(J,I,1)=SLPMIN(J,I,1)*CONVRT
         WRITE(6,3700) (SLPMIN(J,I,1),I=1,ISTOP2)
 3700    FORMAT('0','MIN SLOPE(DEG) ',50(2X,F4.0))
         WRITE(6,3800) (SLPMIN(J,I,2),I=1,ISTOP2)
 3800    FORMAT(' ','MIN RANGE(M) ',2X,50(2X,F5.1))
         WRITE(6,3900) (SLPMIN(J,I,3),I=1,ISTOP2)
 3900    FORMAT(' ','MAX RANGE(M) ', X,50(2X,F5.1))
 4000    CONTINUE
C        OUTPUT DATA ON AZIMUTHS
         WRITE(6,4100)
 4100    FORMAT('1','AZIMUTH',46X,'TERRAIN CHARACTERIZATION',43X,'RTN')
         DO 20000 J=1,NUMAZ
         I=HAZARD(J)
```

```
      GO TO(5000,6000,7000,8000,9000,10000,11000,12000),I
 5000 RTN(J)=1
      WRITE(6,5500) J
 5500 FORMAT('0',3X,I2,5X,'SCAN INDICATES LEVEL GROUND.  TERRAIN '
     1     ,'IS PASSABLE.',61X,'1')
      GO TO 20000
 6000 RTN(J)=0
      WRITE(6,6500) J,MXMISS,RANGE(J)
 6500 FORMAT('0',3X,I2,5X,I1,'  MISSING RETURNS DETECTED BEGINNING',
     1   'AT A RANGE OF ',F3.1,' METERS.  TERRAIN IS NOT PASSABLE.',
     2    23X,'0')
      GO TO 20000
 7000 RTN(J)=0
      WRITE(6,7500) J,RANGE(J)
 7500 FORMAT('0',3X,I2,5X,'NEGATIVE OBSTACLE DETECTED AT ',F3.1,
     1   ' METER RANGE WITH VEHICLE PITCH BELOW A SAFE LEVEL.  NOT',
     2   ' PASSABLE.',10X,'0')
      GO TO 20000
 8000 RTN(J)=0
      WRITE(6,8500) J,RANGE(J)
 8500 FORMAT('0',3X,I2,5X,'POSITIVE OBSTACLE DETECTED AT ',F3.1,
     1   'METER RANGE WITH VEHICLE PITCH ABOVE A SAFE LEVEL.  NOT',
     2    ' PASSABLE.',10X,'0')
      GO TO 20000
 9000 RTN(J)=0
      WRITE(6,9500) J,RANGE(J)
 9500 FORMAT('0',3X,I2,5X,'OBSTACLE DETECTED AT ',F3.1,' METER RANGE'
     1   ,' WITH POSSIBLY HAZARDOUS SLOPE.  TERRAIN WILL BE AVOIDED.',
     2   16X,'0')
      GO TO 20000
10000 RTN(J)=0
      WRITE(6,10500) J,RANGE(J)
10500 FORMAT('0',3X,I2,5X,'OBSTACLE DETECTED AT ',F3.1,' METER RANGE ',
     1   'WITH DEFINITELY HAZARDOUS SLOPE.  TERRAIN IS NOT PASSABLE.',
     2   14X,'0')
      GO TO 20000
11000 RTN(J)=1
      WRITE(6,11500) J
11500 FORMAT('0',3X,I2,5X,'POSSIBLE OBSTACLE DETECTED BUT NOT CLOSE ',
     1     'ENOUGH TO NECESSITATE AVOIDANCE.',38X,'1')
      GO TO 20000
12000 RTN(J)=1
      WRITE(6,12500) J
12500 FORMAT('0',3X,I2,5X,'OBSTACLES DETECTED ARE NOT HAZARDOUS.'
     1     ,'  TERRAIN IS PASSABLE.',52X,'1')
20000 CONTINUE
      RETURN
      END
      SUBROUTINE PITCH(J)
      COMMON/SENSR/BEMRNG,ASMUTH,LANGLE,RTN,KOUNT,ISCAN
      COMMON/TIEUP/THETNU,ALPHA,SLPIN,SLPCRS,SLPCHS,TALLOW
      COMMON/SLOPE/SLPMAX,SLPMIN,ISTOP1,ISTOP2
      REAL SLPMAX(50,50,3),SLPMIN(50,50,3),ASMUTH(50)
      REAL BEMRNG(50),LANGLE(50)
      INTEGER RTN(50)
C     THIS SUBROUTINE CORRECTS CALCULATED OBSTACLE SLOPES TO ACCOUNT
C     FOR VEHICLE ATTITUDE.
C
      DELTA=ASMUTH(J)+ALPHA
      THETA=ATAN(TAN(SLPIN)*COS(DELTA)-TAN(SLPCRS)*SIN(DELTA))
```

```
      DO 100 I=1,ISTOP1
     SLPMAX(J,I,1)=SLPMAX(J,I,1)+THETA
100   CONTINUE
      DO 200 I=1,ISTOP2
     SLPMIN(J,I,1)=SLPMIN(J,I,1)+THETA
200   CONTINUE
      RETURN
      END
```