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THE AEROSPACE CORPORATION

AEROSPACE REPORT NO.
ATR-74 (7908)-1

EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM

CONCEPT DEFINITION FOR THE TRUCK ANTI-HIJACK AND TRAILER SECURITY SYSTEM

Law Enforcement Development Group

January 1974

DEVELOPMENT

Prepared for

NATIONAL INSTITUTE OF LAW ENFORCEMENT AND CRIMINAL JUSTICE
Law Enforcement Assistance Administration
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Contract No. J-LEAA-02573

This project was supported by Contract Number J-LEAA-02573 awarded by the Law Enforcement Assistance Administration, U.S. Department of Justice, under the Omnibus Crime Control and Safe Streets Act of 1968, as amended. Points of view or opinions stated in this document are those of the authors and do not necessarily represent the official position or policies of the U.S. Department of Justice.

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CONCEPT DEFINITION FOR THE TRUCK ANTI-HIJACKING AND TRAILER SECURITY SYSTEM

Approved

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SUMMARY

Aerospace Corporation is currently conducting a program to develop equipment for reducing the incidence of truck hijacking and cargo theft. Nationwide loss to cargo theft in all forms of transporation was estimated by the Department of Transporation to be almost $1.5 billion in 1970*; the portion attributable to motor transport was about $900 million. These crime costs have been increasing at a rate of 17 to 23 percent since that estimate was made.

Figures for direct loss represent only part of the overall cost. The Senate Select Committee on Small Business estimated that, for every dollar of direct loss, the cargo carrier and/or shipper loses an additional $2 to $7 in paperwork and manpower for processing claims and conducting investigations. When these factors are included, total indirect costs of cargo theft to the economy approaches $10 billion annually. The losses are reflected in increased operating and transportation expenses to shippers and carriers and are, ultimately, passed on to the consumer in the form of higher prices. Therefore, reduction in these losses can be expected, in the final analysis, to contribute to reductions in the price of goods to the consumer.

As part of this LEAA-sponsored program to develop the Truck Anti-Hijack and Trailer Security System, a study effort was performed to define the system concept. The study effort consisted of detailed economic and technical analyses of subsystems and components that must be used in any

*The Senate Committee on Small Business estimated that $1.47 billion was lost during 1970 to cargo theft.

cargo protection system. It also made use of in-depth discussions with law enforcement and trucking experts in identifying operational, technical, and cost requirements.

As a result of these activities, a system concept was defined which could incorporate all functions essential to providing cargo protection in trucks. The concept stresses modularity and, as such, it combines inherent cost benefits associated with large quantities of simple parts with the advantages of flexibility, since modules can be configured for a large variety of applications. An added benefit of the concept is that its flexibility makes it compatible with a wide variety of related systems (for status reporting, billing, dispatching, etc.) and also makes it useful for many diverse applications (taxicabs, buses, and public safety vehicles). It is estimated that, in its most simplified form, the equipment associated with each vehicle would be in the range of cost that trucking companies currently incur for mobile radio equipment. It is further estimated that savings from reduced cargo loss would more than pay for this equipment.

CHAPTER I. INTRODUCTION AND OBJECTIVE

A. Introduction

This report defines a concept for a truck anti-hijack and trailer security system which resulted from a LEAA-sponsored task under the Equipment Systems Improvement Program. The aim of the task is to reduce the incidence of cargo theft in the trucking industry. The usual insurance policy covering cargo loss includes a large deductible ($100,000), so that most losses are not covered. Except for unusual large-scale losses, most transportation companies are effectively self-insured. Since most trucking firms operate on very low profit margins, cargo losses due to theft represent a very high percentage of after-tax profits, in some cases up to 50 percent.

A Department of Transportation[†] study indicates that a $1 reduction in cargo claims can provide as much as a $0.50 increase in carrier profits. This can be compared to the fact that a $1 increase in operating revenue usually provides only a $0.02 increase in carrier profits. These figures have led a number of trucking companies, industry associations, and government agencies to exert efforts to reduce cargo theft. While large trucking companies can afford elaborate security services, such as large staffs of private police and the use of cars and helicopters for surveillance, small companies can do little more than improve their locks and hope for the best.

[†] "Proceedings of the 1973 National Cargo Security Conference", U.S. Dept of Transportation and the Transport Association of America, Washington, D.C.

There is no equipment available at present to meet the trucking industry's needs for comprehensive cargo protection. Equipment and devices currently being sold or planned are constrained by either exclusive application to preplanned routes (for the Avcon or the Nelson Trucking systems) by the requirement for engine disabling (as with the "Load Guard" system) or by limits in range (for the "electronic license plate" system). What is needed is equipment that is highly flexible in its application so that it can be applied to many different kinds of operations in various trucking companies. At the same time, there must be a uniformity in design and construction so that per-unit costs can be kept low. It must also be portable, so that only those trucks carrying high-value cargo need be equipped and automatic, thus preventing normal trucking operations from being disrupted.

The Aerospace cargo protection task was initiated in December 1972. In June 1973 a feasibility demonstration of a hijacked truck locator was performed. The demonstration system incorporated features for hijack detection, vehicle control, and engine disabling. The system was designed for trucks operating over a preplanned route and it utilized an odometer as the location sensor.

The demonstration system was exercised in a series of meetings with representatives of trucking and law enforcement organizations. Comments and suggestions made during these meetings led to a more precise statement of system requirements and functions. The meetings were supplemented by attendance at a number of conferences and seminars dealing with cargo loss, transportation security, and vehicle identification.

From these efforts has emerged the concept of a portable, modular set of system elements that can be configured in a variety of ways to accomplish numerous tasks at minimal cost. The system will provide the user with options for performing vehicle disabling, random route location, parked trailer protection, and other functions at his discretion, depending upon the particular task requirements.

While performing the concept definition task, several areas of technology were identified which require further development in order to meet the needs of a cargo protection system. These areas include the development of:

- Rugged, reliable hardware that can be evaluated in actual trucking operations
- Low-cost techniques to locate trucks in urban areas
- Low-profile components, such as antennas, that can be hardened against attack without sacrificing efficiency.

It is planned to address each of these areas in future project efforts.

B. Objective

The objective of this program is to develop a system for determining when a cargo-carrying truck has been hijacked or stolen and for providing information on the identity and location of the truck. Since protection of cargo is the ultimate aim of the program, the effort additionally addresses itself to concepts involving parked-trailer protection, vehicle disabling, and control of access to cargo.

An essential goal of the program is to achieve low cost to the trucking company while maintaining a high level of system effectiveness. This goal will be met by establishing the following design objectives:

- To design the system in the form of simple, general-purpose modules, each of which can be produced in large quantities at low cost.
- To design the system so that it will readily interface with existing vehicles' and dispatchers' equipment with a minimum modification at these interfaces.
- To design the system so that no driver interaction, other than the normal voice communication with the dispatch center, will be required for operation.

CHAPTER II. STATEMENT OF REQUIREMENTS

Functions associated with a truck anti-hijacking and cargo accountability system must meet the requirements of the vehicle owners, the vehicle operators, and the local law enforcement officers. The requirements for any particular application will represent a compromise between the (sometimes conflicting) desires of the various groups and can, therefore, be expected to vary somewhat in each case. It is this situation which has led to a system-configuration concept which emphasizes flexibility.

In general, the concept definition study has provided requirements explained in the following paragraphs.

A. Cost

Trucking companies are not in the business of crime prevention and cannot be expected to reduce their own efficiency with excessive security expenses. Therefore, cost of purchasing and operating a loss-prevention system must be offset by the contributions such a system makes to company profits.

In general, theft-related cargo losses account for about 1 percent of the total gross operating revenue of trucking firms. Since about one fifth of the gross revenue is derived from transporting high-value cargo (that which is most often stolen), it can be estimated that about 5 percent of the gross revenue from high-value cargo shipments will be lost through theft. For example, a company deriving $1 million each year in transporting high-value goods (clothing, liquor, cigarettes, etc.) can expect to lose on the order of $50,000 in cargo thefts. A system which would reduce these losses by 80 percent would save the company $40,000. These savings in turn would increase

the company's profits by $20,000. In order to make it worth the company's while to purchase, install, operate, and maintain the system it should cost no more than about $10,000 to $15,000 per year. Since an average truck can be expected to generate from $150,000 to $200,000 in revenue per year, the system should accommodate about 6 or 7 trucks. In effect, the company could increase profits by investing in equipment costing up to $2,000 per year on each truck. This figure is higher than the estimated cost of equipping the trucks in the fleet with a hijack and theft-prevention system that includes a mobile radio system. Many trucking companies currently equip their trucks with radio transceivers, each costing from $800 to $1,000 to buy and about $100 per year to maintain. These transceivers are mainly for administrative use and provide no protection against hijacking. Informal surveys made by the project personnel have indicated that vehicle hijack prevention equipment with costs equivalent to mobile radio costs would be attractive to the trucking industry.

B. Random Route Location

Use of a random-route system in trucking operations has effect both in hijack prevention and in cargo recovery. Planning of a hijack operation necessitates prior knowledge of the vehicle route and the timetable. Establishment of a route for use with an elapsed distance-location system entails preplanning, with its built-in potential for leakage of route/schedule information. In contrast, the availability of a random-route locator would enable a determination of route to be made at the time of vehicle departure, and for route changes to be made in transit, while maintaining a capability to monitor the vehicle's adherence to the route. The planning of a hijack

also includes rapid concealment of the vehicle or the unloading of its cargo, and recovery is critically dependent on a minimum search time by intercepting law enforcement vehicles. A random-route locator is essential to the successful intercept mission.

The use of a "homing" signal to assist in locating a truck has been considered by several organizations. In one configuration, each truck would be equipped with a coded transponder. An interrogator unit, carried by the search vehicle, would emit a signal addressed to the code of the missing truck. When the truck transponder recognized this code, it would reply with an answering signal. The interrogator would obtain range and bearing information from the homing signal to assist in finding the truck.

This concept is limited in its application, since it does not supply position fixes directly to a base station. Also, an interrogator must come within rather close range of the transponder in order to get reasonably accurate measurements. This latter factor was analyzed to obtain estimates of required interrogator-search time based on an assumed system range of 0.5 miles. The missing truck was assumed to be within a circle of a given radius (based on time elapsed since its departure from a known location). Two search methodologies were considered: first, a relatively slow (30 mph) search of a grid pattern; second, a high-speed search (90 mph) in a continuous spiral starting from the known departure point.

Analysis results shown in Figure 1 indicate that, if the missing truck were known to be within a circle of radius 10 miles, the high-speed search would require almost 2 hours (worst case) and the low-speed search would

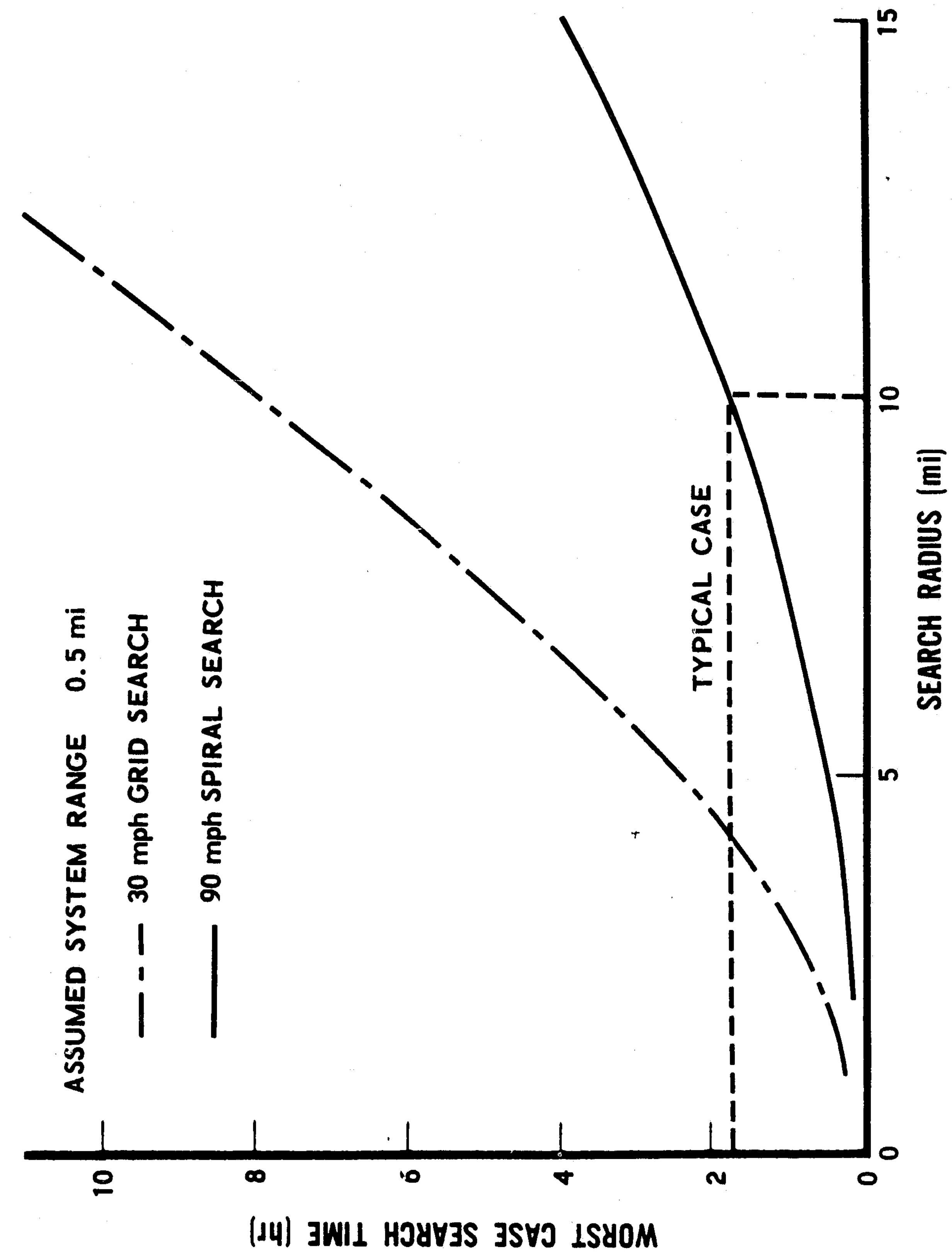

Figure 1. Transponder System - Search Time from Last Known Location

take about 8 hours (worst case). The figure further shows the advantages to be gained when the transponder is used in conjunction with a random locator. Even if the locator system were able to position the missing vehicle within a circle of only 1 mile, search time would be reduced to a few minutes.

C. Communication

The system must not require high usage of the communication channel: land mobile communication channels are in critically short supply and priority usage is assigned to emergency and public safety vehicles. Ideally, the locator system should be such that the vehicle would transmit only when an alarm situation was encountered or when queried by the dispatcher. The transmission should be a short, voice-bandwidth signal containing position information or data from which vehicle position could be computed.

The success of the system is highly dependent upon the integrity of the communications link between the truck and its base station. For this reason, it is to be expected that the communications system will be a target for hijackers. Probably the most vulnerable part of the communications system is the vehicle antenna. Its prominent position and physical weakness make it likely that it would be attacked in a robbery attempt.

These factors led the project staff to investigate the feasibility of equipping vehicles with low-profile antennas, which could be made unobtrusive and possibly "hardened" against attacks. Field tests were run on two low-profile antennas--the loop-monopole antenna (hula hoop) and a multiturn loop, mounted on the roof of a panel truck. Test results presented in detail in Appendix A show that the loop-monopole antenna can meet operational requirements.

D. Range

The system should supply broad area coverage. Most trucking companies operate on a city-wide basis, so that their area of activity would normally extend from 50 to 400 square miles. In this context, a system that may be adequate in a confined area (less than 50 square miles) would not have wide application for hijacked truck location.

E. Hijack Detection

The system must provide an alarm indication when it detects unauthorized intrusion into the driver's cab or into the cargo compartment. Since control of vehicle status is exercised by the dispatcher, the dispatcher can function only as long as the communication link between the vehicle and the base station remains intact. In situations where high-value cargo is being transported, the communication link can periodically be tested either automatically or through established operational procedures.

The system must further provide an alarm indication when it detects any deviation from a planned route. Discussions with police and trucking security officers have revealed that experienced hijackers devise methods for gaining entry to the vehicle without being detected. It is also conceivable that these hijackers could hold the driver hostage and force him to make the correct responses to dispatcher queries. In this situation, detection of the crime could be made only from observations of vehicle movement. Wide, unexplained deviations from the normal route, or unscheduled stops, would alert the dispatcher that a robbery was conceivably in progress. While this technique can be employed in a limited fashion with a single odometer

"elapsed distance" locator, its full utilization requires installation of a random locator system.

F. Driver Interaction

Trucking company executives have reported a general lack of success with equipment that calls upon the driver to independently perform some manual operations. This system should not require driver assistance.

CHAPTER III. CONCEPT

The general concept consists of installing a low-cost, multipurpose cargo protection unit on each vehicle (truck or trailer) selected for carrying high-value cargo. These units will be portable "packages" configured specifically for the particular application.

So that installation of these units will be simple and fast, a large segment of the radio-equipped vehicles in a trucking fleet will be provided with interface attachments. Such attachments will be very low cost and will allow the anti-hijack "package" to be installed quickly on any selected vehicle. The "package" will consist of the electronics to provide position determination, vehicle status control, hijack detection, and data communication interface. The package may also provide for vehicle disabling as a user option. Furthermore, the package will interface with the vehicle communication and power equipment, door sensors, and antenna equipment. If desired by the user, the package may also be connected to engine equipment specially installed to provide for the disabling function. Provisions can also be made for the installation of an autonomous communications and power package.

It is envisioned that the electronic package will consist of several modules, each providing for such specific functions as hijack detection, vehicle location, engine disabling, etc. The types of modules chosen for a given application will depend, of course, upon the functions needed for that task. For example, the module for vehicle location may consist of either a simple preplanned route location sensor or a random route locator. In either

case, the interface would be the same, so that modules could be used interchangeably.

The heart of the vehicle's electronics is the data control module. This module provides logic to determine when the sensor data should or should not be interpreted as a hijack attempt. It also controls data transmission to and from the dispatcher. The data control module defines certain states or modes in which the vehicle functions: for each state, the vehicle may perform specific functions and operations. If the vehicle deviates from these functions, the dispatcher is alerted and can prepare to take action. For example, if the vehicle is in the mode defined for terminal or loading operations, it may be parked and maneuvered at will. The doors may be opened and closed without generating an alarm. If the vehicle electronics detected excessive movement, however, (indicating that the truck is being driven from the terminal) the control module would initiate an alarm sequence.

The inherent flexibility of the data control module makes it adaptable to the use of programmable logic operations, timing sequences, and other techniques to reduce false alarms and to detect tampering. A possible logic sequence could also prevent status changes being made without dispatcher approval. Before a truck with a high-value cargo could leave the terminal, the driver would request the dispatcher to put the truck in an "arm" mode, a condition in which the truck may move but the doors may not be opened. At the delivery point the driver would again contact the dispatcher and request a "safe" condition. This state would allow the doors to be opened for driver exit and cargo unloading. During the trip there need be no communication between the driver and the dispatcher. Any attack on the truck would

immediately cause the control module to transmit vehicle location, identification and status. The dispatcher could obtain the same information by addressing the unit.

Each data control module will have an identification number. When the module is installed in a truck, this number will identify the truck to the dispatcher. All commands from the dispatcher to the vehicle will use the number to differentiate between this truck and all other trucks in the fleet. The module may have switches that enable the installer to match the unit ID code with the number painted on the roof of the vehicle. This would facilitate correlation between the monitoring of the radio transmissions from the truck and visual surveillance from an aerial vehicle.

When the vehicle unit is to be used to provide cargo protection on a parked trailer, the normal mobile radio equipment will be unavailable. In this case the unit will be configured with the addition of a module to provide power and communications capabilities. In this configuration the unit will sense trailer motion, vibration, or door openings. If intrusion or tampering is detected, an alarm transmission will be initiated. This transmission will be low power and will be intercepted by a local receiver, from where it will be relayed to the local police and/or security force. The vehicle unit will also respond to interrogations from the local unit to verify the security of the trailer. Similarly, the vehicle unit may be equipped with a high-power transceiver where a protected trailer is being drawn by a tractor unit which has no communications equipment.

CHAPTER IV. EVALUATION OF EXISTING TECHNOLOGY

Vehicle location is an essential function of an anti-hijacking system, since it enables both dispatcher and law enforcement personnel to detect a hijacking event and to arrive quickly at the scene. In addition to trucking fleet operators, police and fire departments, municipal services, public utilities, taxi fleet operators, and other types of users are actively interested in vehicle location. While not all of these organizations are compatible in terms of vehicle location requirements, filling the general needs of the widest possible user population should be a primary objective in designing any approach to the problem. Such an approach would reduce cost by increasing volume and would also minimize possible interference between competing systems.

Personnel involved in this project have investigated and evaluated a number of automatic vehicle location systems. Since cost is the overriding concern to trucking companies, this factor was used as a basis for comparing various location systems. Costs are necessarily relative since they are functions of fleet size, coverage area, accuracy, and similar factors. The comparisons are reasonable, however, since any assumptions of values related to these factors were applied consistently to each case.

Position determination systems were divided into four functional categories. Table 1 lists the systems based on vehicles receiving signals from fixed transmitters and measuring time differences between these signals. Since discrete values of time delay between transmitters define hyperbolas,

Table 1. Relative Costs for Hyperbolic Position Determination Systems for Truck Location

System	RELATIVE COST			
	Per Vehicle	Base Station	Other	Comments
Decca	High	Medium	High	Requires installation of transmitter systems for each major population area
LORAN	High	High	Very High	Requires installation of transmitter systems for each major population area
Omega	High	High		Ocean/air navigation system not suitable for urban areas .
AM Phase-Lock	Medium	Medium	Low	Uses commercial AM stations, development needed

these position-determination systems are known as hyperbolic systems. They include such various air and ocean navigation systems as Decca, LORAN, and Omega. The systems require locating large, complex, expensive, special-purpose transmitters within range of the vehicle receivers; and the signal processing functions require vehicle electronics that tend to be expensive. Operation in urban areas must be assisted by placing reference receivers at frequent intervals throughout the area to enable local propagation anomalies at the base station to be corrected.

Hyperbolic systems have been developed for airborne and shipboard use. Some development has been performed to modify LORAN C receivers for vehicle use, although the equipment still requires further development.

The AM phase-lock approach provides the dual benefits of low vehicle cost and low transmitter cost. This system provides relative position from a starting point, however, and must be periodically re-initialized. It also requires some development effort. (This concept is discussed in greater detail in Appendix B.)

The second category of location systems (Table 2) includes systems that rely on measurements made of vehicle transmissions. These measurements are made simultaneously by several fixed receivers and may determine either time-of-arrival or direction. The time-of-arrival or trilateration technique is more expensive but also more accurate than the direction-finding or triangulation technique. Both techniques have the disadvantage of requiring each vehicle in the fleet to transmit for a period of time sufficient to allow receivers to provide a measurement. For a pulse-type trilateration system, the requirement is particularly unfavorable since the transmission must be very wideband (10 MHz).

In general, it may be said that trilateration is too expensive in its present state of development and requires too much dedicated bandwidth to be useful for trucking firms. The triangulation method, while cheaper, is too inaccurate even for trucking applications. Direction errors of only 1 degeee would produce unacceptable location errors and, in an urban environment, multipath effects make direction errors of 90 degrees a common occurrence. Both methods would require extensive development before they could be implemented in trucking fleets.

The third category of location systems is termed proximity systems. The two types of proximity systems are the signpost transponder and signpost transmitter, respectively. The relative costs of these systems (listed

Table 2. Relative Costs for Centralized Position Determination Systems for Truck Location.

System	RELATIVE COST			
	Per Vehicle	Base Station	Other	Comments
Trilateration	High	Medium	Very High	Considerable development is still needed to assess accuracy and reliability
Triangulation	Medium	Medium	High	Multipath effects result in unacceptable data accuracy and reliability

in Table 3) point out that the signpost transmitter requires much less in terms of communication capabilities. (This system is discussed in detail in Appendix C.)

The fourth category of vehicle location systems makes use of dead-reckoning techniques. The most prominent approaches in this category are

Table 3. Relative Costs for Proximity Position Determination Systems for Truck Location.

System	RELATIVE COST			
	Per Vehicle	Base Station	Other	Comments
Signpost Transponder	Low	Low	Signpost Cost + Data Collection Network + Central Computer	Requires high-capacity data link from each interrogator to central computer
Signpost Transmitter	Low	Low	Signpost Cost depends upon density and area of coverage	Density and spacing of signposts can be selected to individual municipalities' requirements

shown in Table 4. These approaches illustrate the various tradeoffs between base-station complexity and vehicle complexity. At one extreme is the fully militarized navigation system wherein the vehicle is self-contained and independent. As shown, vehicle hardware in this case tends to be prohibitively expensive. At the other extreme is the concept which puts only the basic compass/odometer sensors in the vehicle and transmits all sensor data to the base station for computation and mapping. This approach minimizes vehicle costs but requires a large base-station expense and a high usage of mobile radio communication for data transfer. Both of these factors severely limit the approach to relatively large fleets that have priority claims for channel use, such as large city police departments.

Table 4. Relative Costs for Dead-Reckoning Position Determination System for Truck Location

System	RELATIVE COST			
	Per Vehicle	Base Station	Other	Comments
Compass/ Odometer	Medium	High	-	Requires high capacity data link from vehicle to base station
Differential Odometer	High	Medium	-	Poor long-term accuracy
Military Navigators	Very High	Low	-	Not tested for urban operation
Compass/ R .te Gyro/ Odometer Hybrid	Medium	Low	-	Further development work is required to verify analytical results

The accuracy performance of the dual or differential odometer system suffers from the property that wheel slippage of only 1 inch creates a heading-angle error of about 1 degree. The differential odometer provides measurements of rate of change in heading angle, and these errors are accumulated. The error accumulation causes a drift from the true direction in indicated heading angle, and this significantly increases the location error magnitude as the distance traveled increases. Several attempts have been made to utilize differential odometers in a dead-reckoning system, but all systems showed an accumulation of heading error that reached an unacceptable level within a short period of time.

An attractive compromise for the truck anti-hijacking location system would make use of low-cost sensors and a simple computational capability within the vehicle. While this equipment's lower accuracy would not allow its use in a self-contained configuration, it could be supplemented with a low-cost, low-density signpost distribution. (This configuration is analyzed and simulation data are presented in Appendix D.)

CHAPTER V. SYSTEM DESIGN

Elements which make up the Truck Anti-Hijack and Trailer Security System are shown schematically in Figure 2. The equipment is shown divided into subgroups based upon geographical location. Four subgroups are identified: base station equipment, vehicle equipment, wayside equipment, and equipment existing in the operating environment and which can be used (with some modifications) to assist in the vehicle-location function.

A. Base-Station Equipment

The function of base-station equipment is to receive and maintain data on the operation of a trucking fleet, particularly on those trucks carrying high-value cargo. Data consist of vehicle status and location and can be compared to the planned operation of a particular vehicle. Unexplained deviations from the plans can be detected by the dispatcher and can be interpreted as an alarm condition.

The base-station equipment can vary widely in terms of complexity and cost, depending upon the number of trucks in operation and the degree of control to be exercised over each truck. For a small fleet relatively simple base-station components will suffice. The signal decoder and display unit coupled with a printer and wall map, such as was used in the demonstration* system, should be adequate for a large portion of the trucking industry. The equipment could also include a polling feature that would automatically generate vehicle queries in some predetermined sequence and at a predefined

*N. A. Mas, Feasibility Demonstration of a Truck Anti-Hijacking System, TOR-D073(3658-02)-1, The Aerospace Corporation, July 1973.

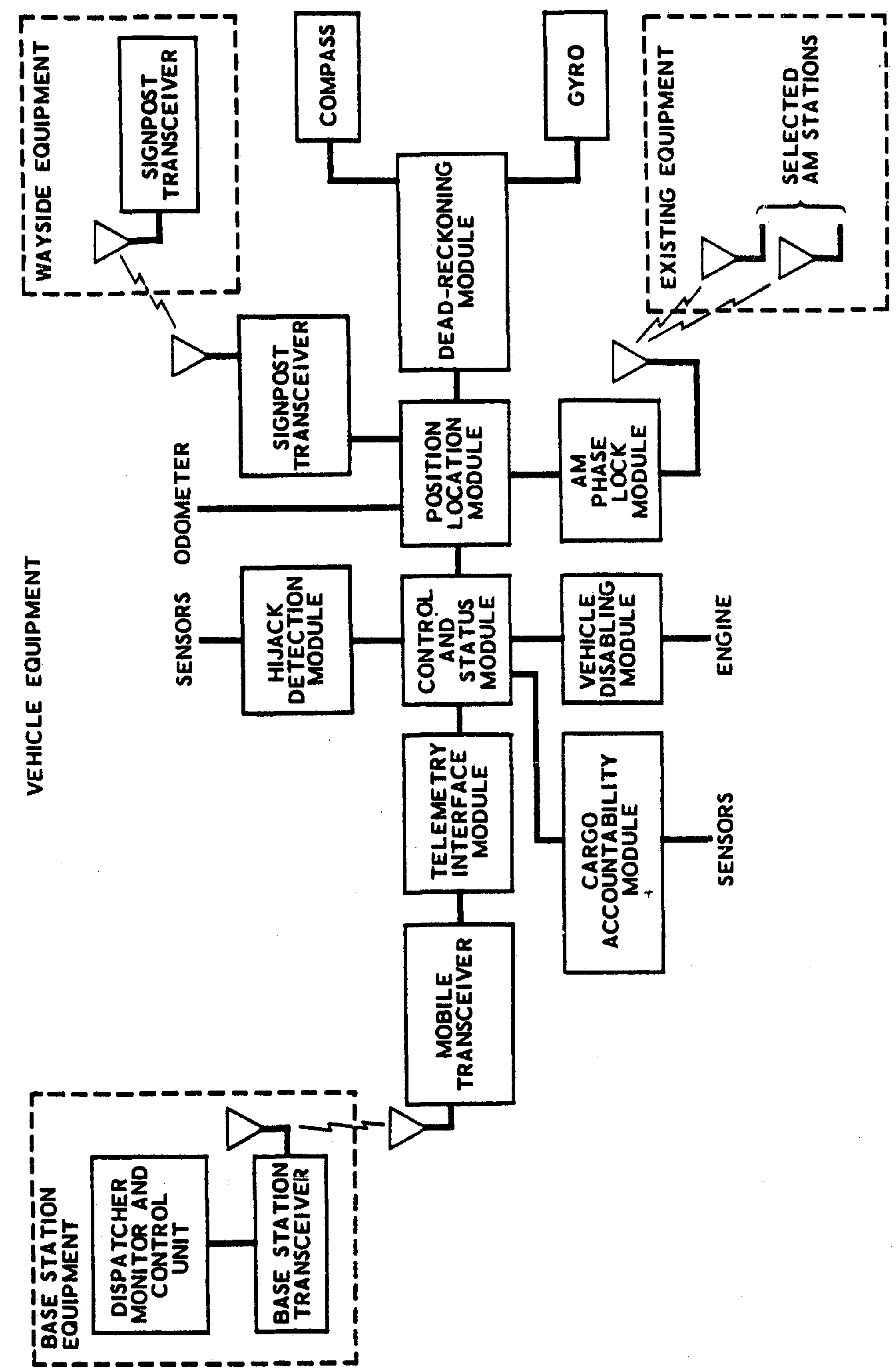

Figure 2. Block Diagram of the Truck Anti-Hijacking System

rate so as to obtain vehicle status without dispatcher intervention. Even if a simplified radio system were utilized for random vehicle location, position fixing could be a simple, graphical procedure the dispatcher could perform manually. The total cost for equipment needed to implement this configuration has been estimated to be on the order of $1,500.

In cases where there is a large number of trucks, or where the trucks make frequent pickup and delivery stops (requiring dispatcher attention), the base station equipment could be supplemented with a small minicomputer. Such a machine would be programmed to perform automatically all position-fixing calculations or procedures and print out the nearest street locations. The machine would also reduce dispatcher workload, process location data, and print out summaries of each vehicles' travels during the day. The computer could provide a hijack-detection capability by automatically checking vehicle position for deviations from its assigned route. Such a computer with its associated interfaces and peripherals would be expected to add about $8,000 to $10,000 to the base-station cost.

B. Vehicle Equipment

Figure 2 shows the vehicle equipment in its most expanded form. In reality, it would contain some subset of the indicated equipment. For example;

- The vehicle may or may not contain the vehicle-disabling module.
- The vehicle may contain either the dead-reckoning module or the AM phase-lock module for position location, but not both.
- If accurate position location were not considered critical, the vehicle may contain only the odometer and signpost transceiver module for position location.

Vehicle equipment modules that would be included in any configuration are the data control and status module, intrusion sensor module, and the location sensor module.

- The data control and status module controls the system operation and makes all status decisions.
- The intrusion sensor module interfaces vehicle hijack sensors to the data control and status module. These sensors may be door switches, acoustic and proximity detectors, or driver-response signals. All signal conditioning, thresholding, and processing will take place in the module.
- The location-sensor module accepts data from one of several sources and converts these data to vehicle location information for subsequent transmission to the dispatcher. The odometer count (which is converted to elapsed distance) and the data obtained when the vehicle passes a proximity unit are the basic input for the odometer system in the location module. Output from each of these units is a unique code that identifies the location of the transceiver. When this code is received it is stored in the location module, and the odometer counter is reset. Whenever the vehicle is queried by the dispatcher, the code of the last proximity unit passed and the distance travelled since that passing are sent to the base station. In this way the approximate location of the vehicle can be maintained. The ability of this configuration to accurately position the vehicle is highly dependent upon the spacing of the proximity units.

In situations where a high degree of accuracy over a large area is required, the number of proximity units (and hence, the system cost) may become excessive. In these situations, vehicle location equipment can be employed to provide accurate vehicle-position fixes between signposts.

A detailed analysis of truck anti-hijacking requirements for vehicle location and of the techniques in use planned for automatic vehicle monitoring (AVM) has identified two approaches that may be suitable for the location function. These two approaches are indicated in Figure 2 as the dead-reckoning module and the AM phase-lock module. Both approaches will be subsequently explained in detail.

Briefly, the dead-reckoning approach makes use of the linear estimation theory to combine the output of relatively inexpensive heading and distance sensors in obtaining position. While position error increases with distance, the increase is relatively slow and enables the use of wide-spaced signposts to keep the error in bounds. The AM phase-lock approach uses the strong carrier signals of AM broadcasting stations to form a hyperbolic location system. The several carrier signals are detected coherently, and difference counts are derived between pairs of carriers which indicate position relative to a starting point. This approach also requires widely spaced signposts to facilitate re-initialization in cases where the counting of carrier cycles is interrupted by the loss of one or more signals.

The countermeasures module will contain sensors for detecting unauthorized tampering with the system (removal of the vehicle unit, severing of interface cables, etc.). Any detection of tampering will cause an alarm to be initiated.

The two remaining modules shown in Figure 2 are the vehicle-disabling module and the cargo-accountability module. These modules would be options to the standard package and would be added for particular users or applications. The vehicle-disabling module would be triggered by the control and status module when an alarm condition was encountered. The disabling may take the form of engine disruption by interfering with the ignition or carburetor system. If the system is installed on a trailer, the vehicle-disabling mechanism may operate on the braking system or on the tractor hookup mechanism. Any mechanism of this type would be designed with a safety override to prevent accidental operation when the vehicle was in motion.

The cargo-accountability module is a general purpose capability which allows data input to the control and monitor module regarding the quantity and condition of the cargo. This feature makes provision for future extension of the system to incorporate cargo security functions.

C. Wayside Equipment

The wayside equipment consists of a number of proximity units spaced at intervals over the geographical area covered by the system. The proximity unit located externally to the vehicle serves two purposes. When positioned at selected locations throughout the city, it serves as a signpost that signals the present position to the vehicle. When terminal protection is required, minor modifications to this unit will make it suitable for use as a local alarm detector. The unit will be placed in the terminal and connected to the facility security alarm system, which is routed either to a private security service or to the local police department. The trailer unit will be activated so that the

control and status unit will transmit an alarm via the vehicle proximity unit rather than through the mobile radio.

D. Existing Equipment

This category includes equipment that is not directly part of the system but which supports the system operation. In particular, the AM broadcast stations, modified to produce stable carrier signals, would be in this category. (This equipment is discussed in more detail in Appendix D.)

As part of the analysis effort, costs of various system approaches to truck location were evaluated. This analysis revealed that, for a given system accuracy, the two overriding parameters affecting system cost are fleet size and coverage area. The three most promising locator concepts were examined for various fleet sizes and coverage areas. These concepts were: high-density signpost, hybrid dead reckoning, and AM phase lock. The last two concepts were assumed to be supplemented by a low-density signpost array. In this analysis a high density system is defined as one having a density of at least ten signposts per square mile. A low-density sighpost array would have no more than one signpost per square mile.

Figure 3 shows results from the effort to postulate a system accuracy of 400 feet. The figure indicates that for very large fleets, or where the density of vehicles in an area is high (greater than about two or three per square mile), a high-density signpost system is the most cost effective. This is due to the low cost of vehicle equipment using this approach.

For very small fleets, the figure indicates that a hybrid dead-reckoning system plus low-density signposts would be the most inexpensive approach. In this case the higher costs for vehicle equipment is more than made up for by reductions in the number of signposts needed.

Figure 3 shows that for intermediate cases (i. e., where vehicle density is between 0.2 and 2.0 vehicles per square mile), vehicles equipped with AM phase-lock locator systems would be the most cost effective

AREA	NO. OF VEHICLES EQUIPPED			
	1-75	75-500	500-1000	>1000
400 sq miles LARGE CITY	HYBRID DEAD RECKONING + LOW DENSITY SIGNPOST	AM PHASE LOCK + LOW DENSITY SIGNPOST	AM PHASE LOCK + LOW DENSITY SIGNPOST	HIGH DENSITY SIGNPOST
200 sq miles MEDIUM SIZED CITY	HYBRID DEAD RECKONING + LOW DENSITY SIGNPOST	AM PHASE LOCK + LOW DENSITY SIGNPOST	HIGH DENSITY SIGNPOST	HIGH DENSITY SIGNPOST
50 sq miles SMALL CITY	HYBRID DEAD RECKONING + LOW DENSITY SIGNPOST	HIGH DENSITY SIGNPOST	HIGH DENSITY SIGNPOST	HIGH DENSITY SIGNPOST

Figure 3. Cost Effectiveness for Various Approaches to Locating a Hijacked Truck.

technique. As before, the large coverage area mitigates against high-density signposts. Furthermore, lower costs for AM phase-lock vehicle hardware, relative to the hybrid dead-reckoning approach, offset the higher base-station costs associated with the hyperbolic system.

To estimate the cost for implementing a truck anti-hijack and trailer security system, a scenario will be assumed in which a number of small trucking companies cooperate to install the system in a medium-sized city. If ten companies each having ten equipped vehicles is assumed, Figure 3 indicates that a locating system using an AM phase-lock locator combined with a low-density signpost would be the most cost-effective approach.

If the area to be covered extended about 200 square miles, and if approximately one signpost was needed per square mile, the total signpost cost would be $10,000 for a signpost unit-cost of $50 (including installation). The cost of equipping four AM broadcast stations with units for stabilizing the carrier frequencies would be $40,000. The cost of AM phase-lock equipment (vehicle-location module) would be about $300 for each vehicle. The size of the trucking companies under consideration would postulate a simple manual procedure for position-fixing, and the base-station cost would be about $1,500.

Additional vehicle hardware for handling functions of intrusion detection, data control, signpost signal detection, and interfacing would cost an estimated $250 per vehicle. The basic interface hardware installed on the truck or trailer (and into which the cargo protection package would be plugged) would cost an additional $50 per vehicle.

The final system cost to an individual trucking company would be as follows:

	Item	Cost
1.	Assigned portion of signpost (10% of $10,000)	$ 1,000
2.	Assigned portion of AM station equipment (10% of $40,000)	$ 4,000
3.	Base Station Cost	$ 1,500
4.	Vehicle interface cost-assume 30 trucks and trailers equipped (30 x $50)	$ 1,500
5.	Basic cargo protection package (10 vehicles x $250)	$ 2,500
6.	Location modules (10 x $300)	$ 3,000
	Total Cost	$13,500

The total cost figure is roughly equivalent to one third of the expected cargo loss associated with operating a fleet of 30 to 40 trucks for one year.

CHAPTER VII. CONCLUSIONS AND PLANNED DEVELOPMENT

The concept definition report has documented the major findings and results of the Truck Anti-Hijack and Trailer Security Program accomplished through November 1974. Work performed included design and fabrication of a demonstration system; evaluation of vehicle location techniques, including identification and analysis of approaches that are most cost effective for trucking applications; interaction with trucking and law enforcement personnel and extensive operations; and cost analyses. These efforts have resulted in the evolution of a concept to provide a large segment of the transportation industry with effective protection against theft at low cost. The concept is based upon development of a number of standard modules which can be combined in a wide variety of configurations to accomplish diverse tasks. In essence, the system can be tailored to the specific need of a particular trucking company, whether the need be for:

- A very low cost, driver-actuated alarm
- A sophisticated automatic truck or trailer protection system including vehicle location and automatic status maintenance
- Some intermediate configuration.

During the remainder of FY 74, plans are to continue development and evaluation of the vehicle-location techniques whose characteristics are applicable to the trucking industry. At the same time, completion of procurement and award activities is planned with regard to a prototype-development

subcontract. The subcontract will involve product design and development, prototype fabrication, and operational evaluation of an anti-hijack system in a realistic trucking environment. Contract award is expected in FY 74, and task completion is planned for FY 75.

As an ongoing effort, system design and component specifications are being prepared so that the system will constitute an integral part of a general cargo-protection and accountability system currently under study. The ultimate goal of the combined efforts will be to provide overall cargo security for the transportation industry in a simple, cost-effective manner.

APPENDIX A. LOW-PROFILE ANTENNAS

Two antennas were investigated as possible alternatives to the conventional quarter-wave monopole whip antenna commonly used for voice communications on commercial and police vehicles. Both loop-monopole and the multiturn loop have the advantage of low physical profile and can be concealed so as to be less vulnerable to being rendered inoperative in the event of physical attacks by assailants.

Loop Monopole - The loop monopole antenna is shown photographically in Figure A-1, and schematically in Figure A-2. The antenna consists of a 5.29-inch diameter (C-C) loop spaced 1.0 inch over a ground plane. One side of the loop is grounded, and the open-end of the loop has a variable capacitor to ground which tunes the antenna to resonance at any frequency in the 150 to 170 MHz band. The coax feedline is connected 2.75 inches from the grounded side of the loop to achieve the best impedance match.

Radiation from the antenna is predominately vertically polarized with the ground plane in a horizontal plane. The vertical fields are generated by currents on the center conductor of the coax feed, the short conductor between one side of the loop and the ground plane, displacement current through the tuning capacitor and from the electric field between the loop and the ground plane. A second capacitor (C_1) was added in series with the center conductor of the feed line to provide a convenient means for adjusting impedance to a 50-ohm level.

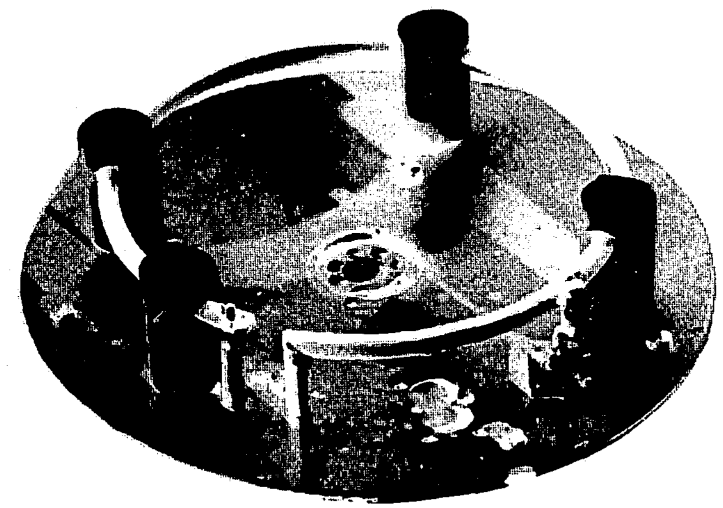

Figure A-1. Photograph of Loop-Monopole Antenna

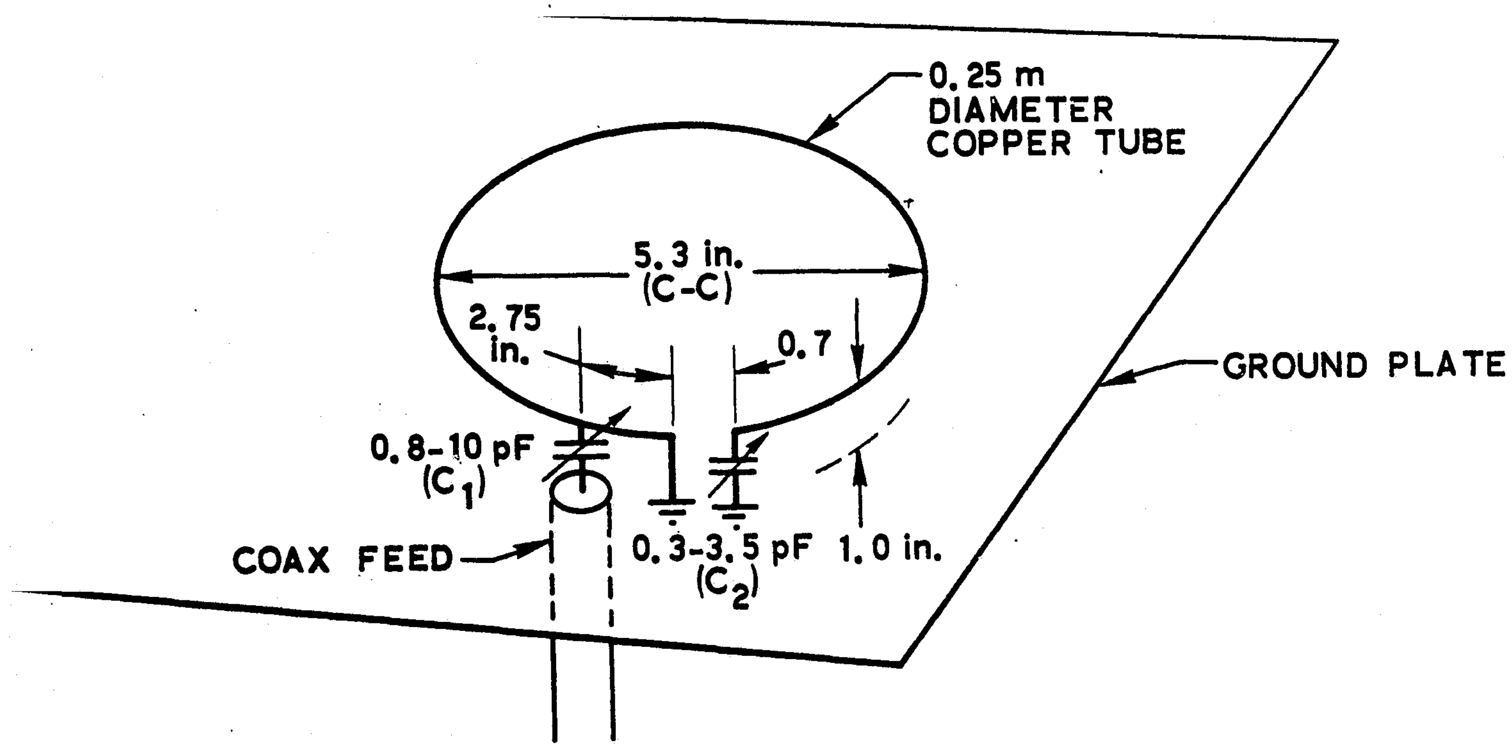

Figure A-2. Schematic of Loop-Monopole Antenna

Patterns were measured with the antenna assembly mounted on the roof of a 1969 Ford panel truck, providing a ground plane approximately 67 x 134 inches (0.9 x 1.8). The relative heights of the loop-monopole and corner reflector resulted in an azimuth pattern cut 3.7 degrees below the horizon. The pattern was measured at midband, 160 MHz, and results are shown in Figure A-3. For comparison, a pattern of a $\lambda/4$ vertical monopole mounted at the same location on the vehicle and with the same power input is included in the pattern plot, thus providing relative gain between the two antennas. Prior to pattern measurement VSWR values were as follows:

loop-monopole: VSWR = 1.34

$\lambda/4$ monopole: VSWR = 1.40

Examination of Figure A-3 shows that the loop-monopole gain is from 1.0 to 2.0 dB or, as an average, 1.6 dB below that of the quarter-wavelength monopole.

Since the antenna structure is electrically small, it has narrow-band impedance characteristics, as seen by the VSWR vs. frequency plot of Figure A-4. Bandwidth is 2.5 percent, or 390 KHz, between 3:1 VSWR points.

A series of VSWR measurements was made to determine the feasibility of tuning the resonating capacitor C_2 to change the operating frequency within the 150 to 170-MHz band and without tuning the impedance adjustment C_1. Results are given by the VSWR vs. frequency plots of Figure A-5. These results show that only C_2 need be adjusted to cover the 150 to 170-MHz band, and C_1 need be adjusted only for the initial midband tuning.

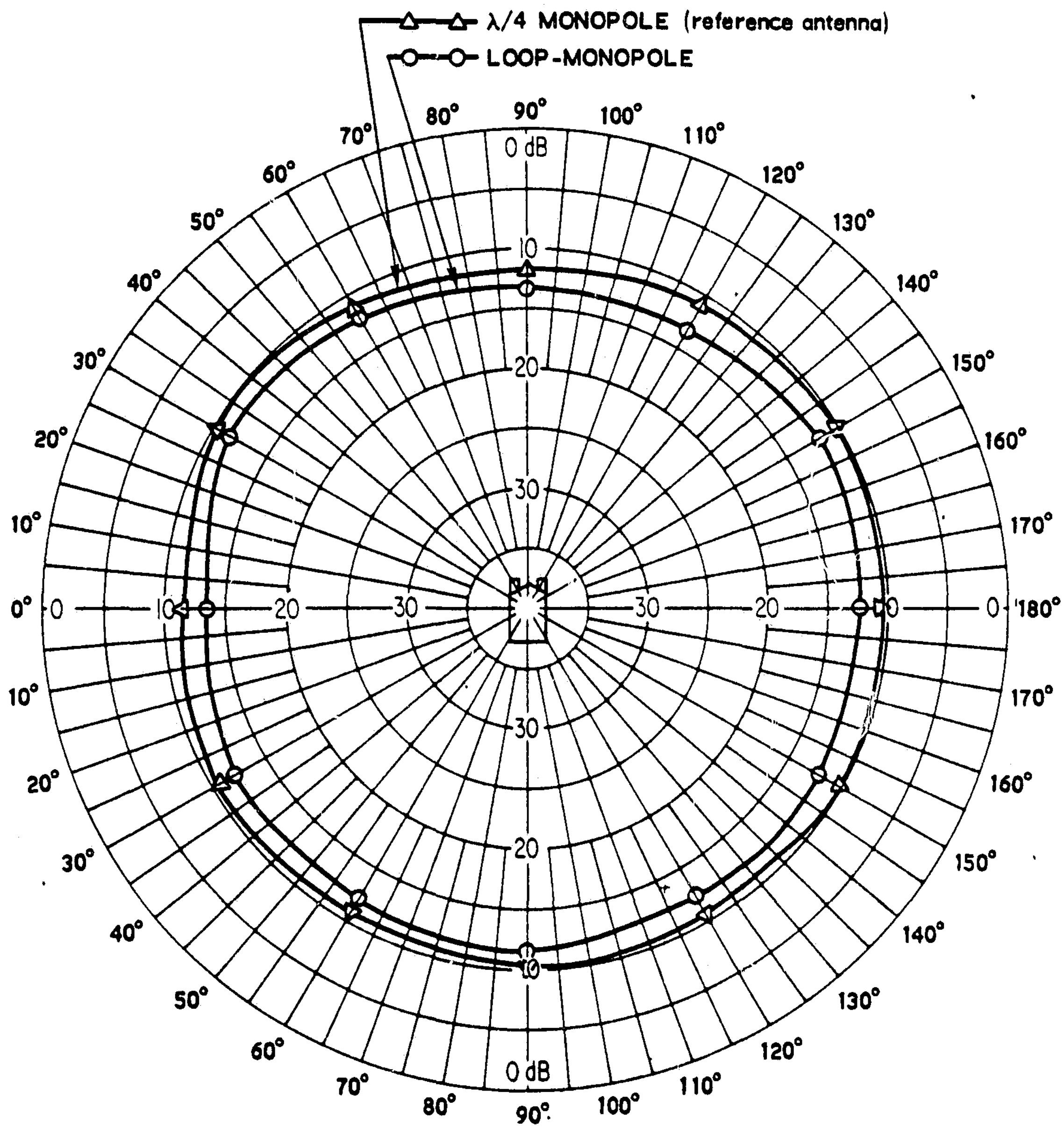

Figure A-3. Azimuth Pattern and Relative Gain of Loop-Monopole Mounted on Roof of Truck

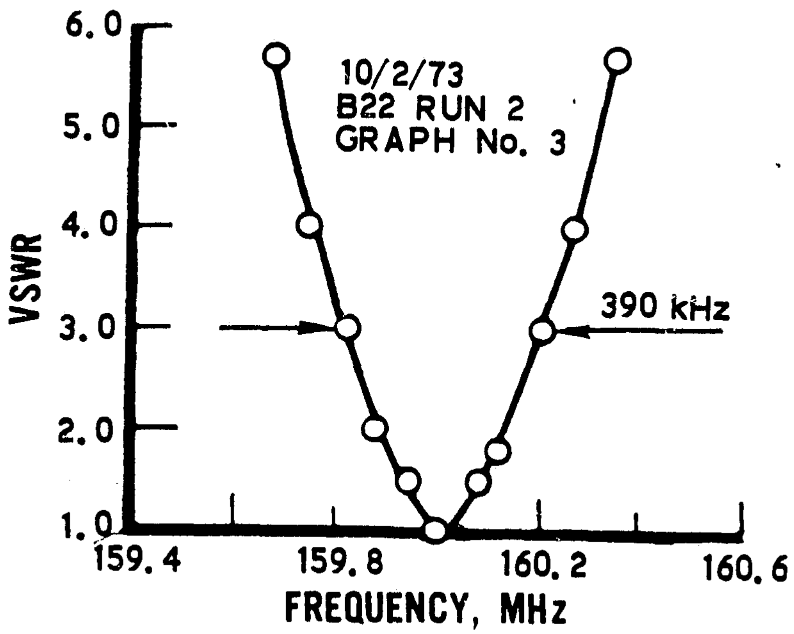

Figure A-4. VSWR vs. Frequency of Loop-Monopole Tuned to Midband

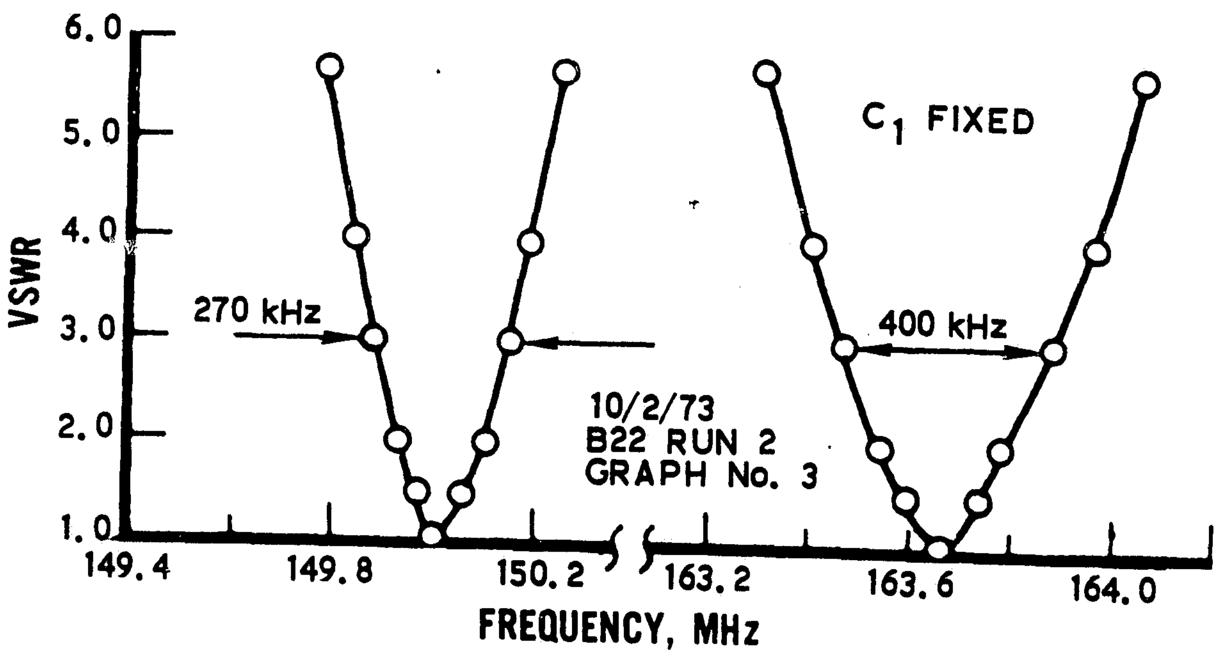

Figure A-5. VSWR vs. Frequency of Loop-Monopole Turned Below and Above Band Center

Multiturn Loop - The multiturn loop consists of 3.5 turns of 0.375 inch wide copper foil wound around a 2.7 x 2.7 x 0.75 inch polystyrene foam core. It is fed at one end against a metal base plate and tuned by a variable capacitor connected between the ground plane and opposite end of the loop. The antenna was originally developed as a shoulder-mounted unit for use by law enforcement personnel and has been included in this test series as a possible vehicular antenna.*

The multiturn loop antenna pattern and gain comparison relative to the $\lambda/4$ monopole are shown in Figure A-6. The pattern was taken with the range instrumentation as shown in Figure A-3. It is seen that in the more favorable orientation (antenna horizontal) the peak gain is 10 to 15 dB below that of the $\lambda/4$ monopole and the pattern contains 30 to 40 dB nulls.

Conclusion - The loop-monopole mounted on the roof of a truck exhibits good azimuth omnidirectionality (±1.0 dB) and has remarkably good efficiency considering its low profile. The gain is approximately 1.6 dB lower than that of a $\lambda/4$ monopole. However, it has the disadvantage of being narrow band. It is expected that special tuning circuits can be utilized for multiple fixed-frequency operations. The multiturn loop was found to have low gain and poor omnidirectional characteristics and thus does not appear to be worthy of further consideration.

It is recommended that if a small, low profile and/or a completely flush antenna is required, further investigations should be devoted to making

*King, H. E., "Investigations of Body-Mounted Antennas for Law Enforcement Application", The Aerospace Corporation, Electronics Research Laboratory, Report No. TOR-0073(3653-01)-2, June 1973.

the loop-monopole fit within a cavity and protected by a dielectric window. The feasibility of multiple-frequency operation should also be investigated.

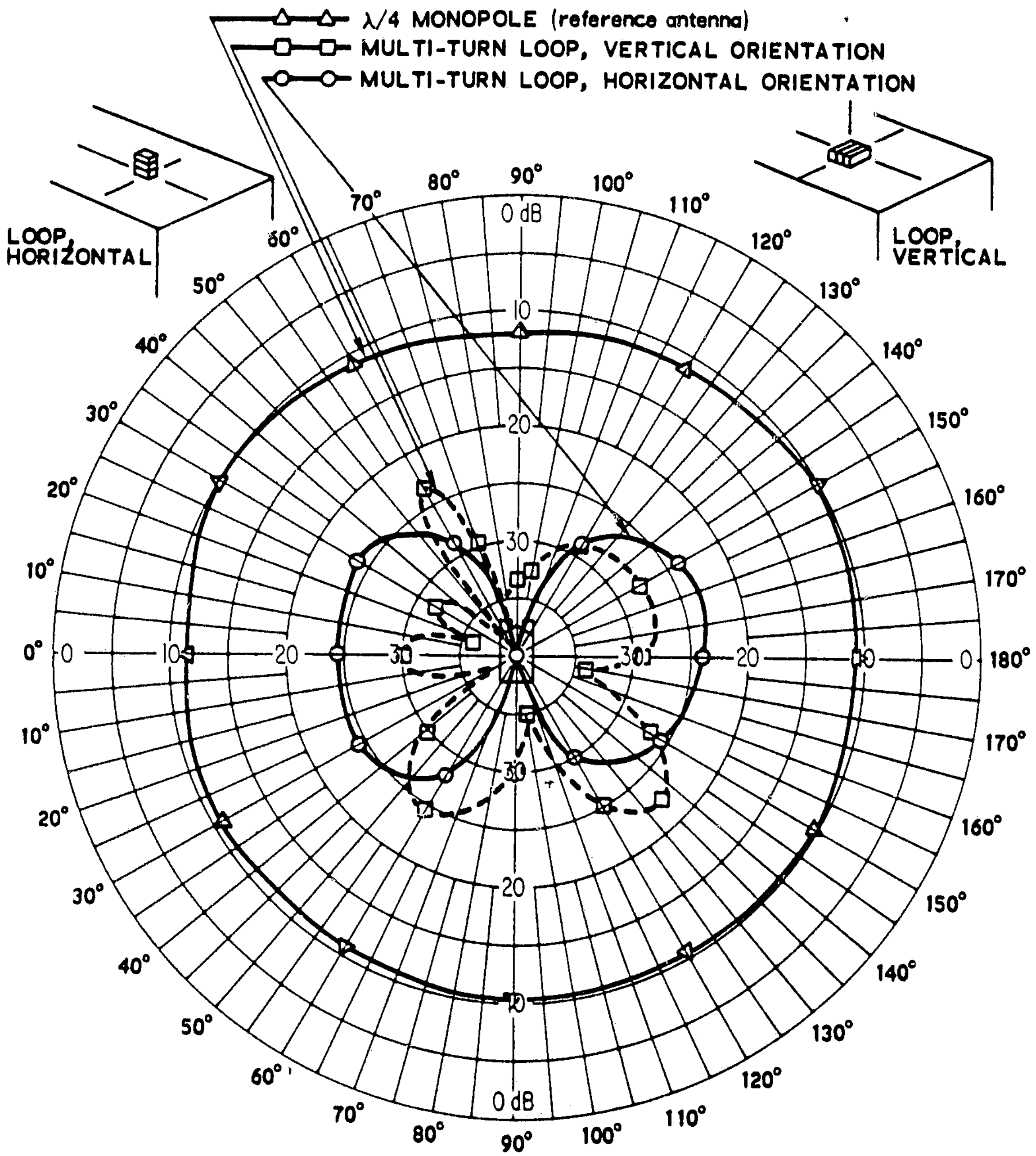

Figure A-6. Azimuth Pattern and Relative Gain of Multiturn Loop Mounted on Roof of Truck

APPENDIX B: AM PHASE-LOCK HYPERBOLIC SYSTEM

This section defines a concept for vehicle location based on measurements taken on local AM radio broadcast station signals. The basic objective is to locate a vehicle by measuring the range difference between the vehicle and three or more local AM broadcasting stations, as shown in Figure B-1. To establish a stable hyperbolic pattern, one selected AM station will have its transmitter carrier frequency stabilized using an atomic standard and the other stations will have their carriers phase locked to the standard. The atomic standard would be a commercial instrument costing between $6,000 and $8,000 and having a stability of one part in 10^{10} or 10^{11} per day. Since each of the AM stations are, in principle, absolutely stable in frequency, one can measure the range difference between these AM stations and directly determine present vehicle position relative to some initial starting position.

A. System Definition

The principal error source which must be evaluated and dealt with is that resulting from propagation anomalies. These anomalies include such problems as multipath signal summation and direct-path attenuation caused by buildings and topography. There does not appear to be quantitative information as to the order of magnitude of these errors at AM broadcast frequencies (535 to 160 KHz). There are data at VHF and UHF frequencies which indicate that typical RF energy ensemble delays in large cities are occasionally on the order of 3 microseconds but can sometimes be as large as 15 to 20 microseconds. If this were also true at broadcast frequencies, it would

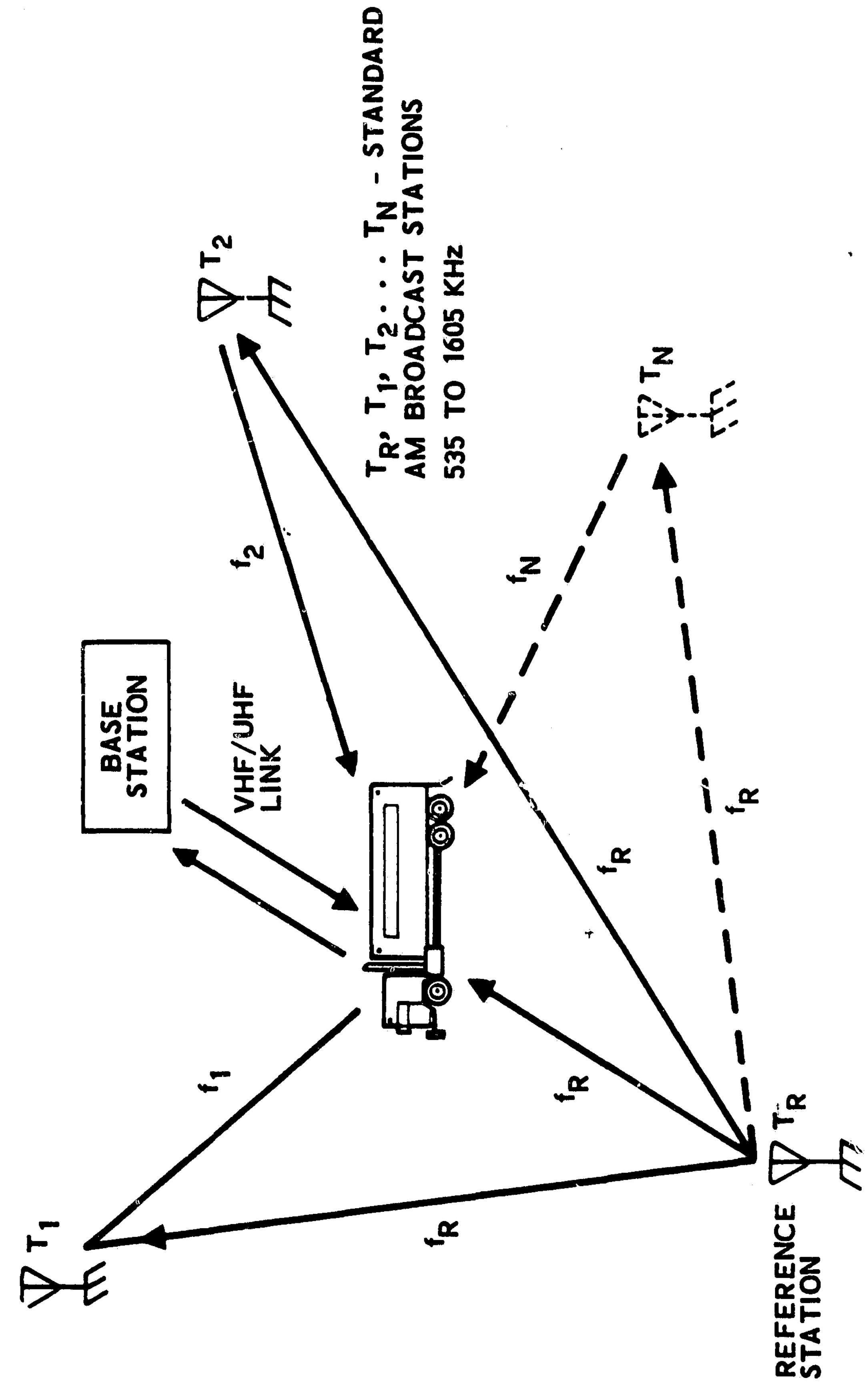

Figure B-1. AM Phase-Lock Location System

imply errors on the order of 3,000 feet or more. On the other hand, there is evidence that there is not as much "echoing" at broadcast frequencies as at VHF and UHF; therefore, resultant errors could be much less than 3,000 feet. By choosing three (or more) broadcast stations at diverse locations, one can also have the advantage of space diversity as well as frequency diversity, and this could significantly reduce errors due to propagation problems. This problem remains to be investigated more thoroughly.

There are various ways in which one can configure the proposed system. Figure B-2 is one embodiment*. Basically, three simple AM receiver channels are always tuned to three different AM broadcast station frequencies. The output of each AM receiver is sent to narrow-band, phase-lock loop (PLL) which, in effect, strips away the audio side bands and locks on to the main RF carrier. In addition, the phase-lock loops are locked in such a manner as to yield a clean output signal at 10 times the input frequency.** This permits simple measurements of time differences of one tenth the interval of one RF carrier cycle. One of the three AM receivers is arbitrarily called the reference channel. This channel is similar to the other two except that the phase-lock loop is set to divide by factor on the order of 100. The output of the reference channel PLL triggers a sharp strobe generator which periodically reads the

* The frequencies and scale factors shown in Figure B-2 are illustrative only and subject to optimization.

**It is important to note that the PLL is operated very narrow band and thereby provides a memory (coast) function to eliminate momentary signal excursions and fade problems.

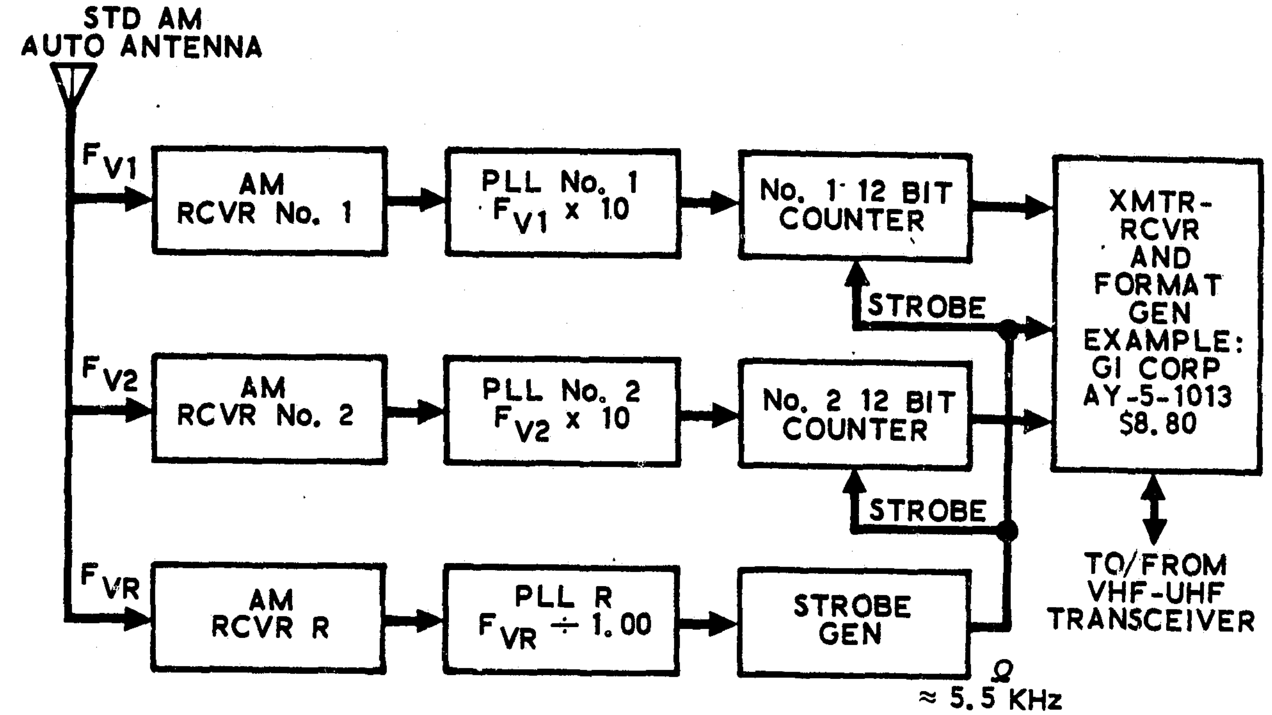

Figure B-2. AM Phase Lock Locator Block Diagram (Base Referenced Vehicle Locator)

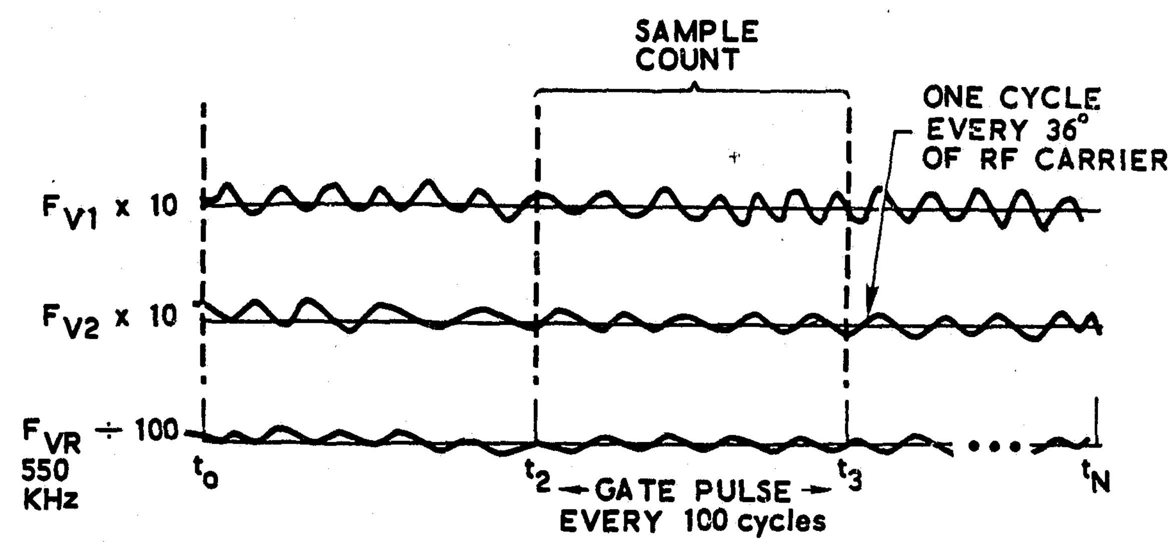

Figure B-3. Timing Diagram AM Phase-Lock Locator

value of a first and second counter. These counters are driven by the first and second PLLs as noted in Figure B-2. Figure B-3 shows typical timing diagrams.

Note that counters No. 1 and No. 2 are operated in module N mode and only the least significant characters are retained; N is a function of maximum resolution and operating radius desired. For a 40-km radius from base station and 20-meter resolutions, N is 2000. A 12-bit counter including parity is suggested. Once initialized at a known location relative to base station, counters No. 1 and No. 2 never stop but are read out (strobed) at a specific point in time t_N defined by the reference AM station; these points t_N are in synchronization with base station readings.

The system measures the change in path length between a first AM broadcast station, the vehicle, and the reference AM broadcast system. This gives a first hyperbolic line of position. Secondly, the system measures the change in path length between a second AM station, the vehicle, and the reference AM station. This gives a second hyperbolic line of position. This process results in a unique vehicle location plus one ambiguity. The ambiguity can be easily eliminated because of prior knowledge of vehicle position. Computationally, this concept is similar to LORAN and other hyperbolic position determining systems.

Another way of describing this concept is to imagine a string connecting the first AM station, the vehicle, and the reference AM station. As the vehicle moves, the length of this string changes; the system measures this change. A similar string connects the second AM station, the vehicle and

the reference AM station. The counts accumulated by the vehicle system can be translated into the amount by which the length of the string changes. The distance values can then be used to calculate the magnitude and direction of the change in position.

A possible system operating procedure is as follows. The system in the vehicle is initialized to some known location by first inserting the correct number into the counters then immediately connecting the counters to their PLL. As the vehicle moves, or due to instabilities, these counters will change. The base station polls each vehicle periodically via the existing VHF/UHF transceiver in the vehicle to determine automatically the reading of each counter, vehicle address, and other pertinent information. The base station receives the reply via the vehicle transceiver. A message of about 36 to 48 bits in length will probably be adequate per reply. The entire inquiry/reply could be done in about 15 to 20 milliseconds. Thus, polling could be done at a rate of about 60 vehicles per second.

The actual vehicle-locating operation would be done manually using a simple graphical procedure or a small computer could be interfaced directly with the communications link to automatically calculate the locations.

An attractive option would be to have the base station VHF/UHF communications receiver automatically sense the absence of any conversations on the air and insert rapid polling signals in between ordinary vehicle-base conversations. In this way one could use the existing communication channels and not require a special channel for vehicle location. For example, using this interleaved method, a fleet of 100 vehicles could be sampled on the

average of every 15 seconds without occupying more than 10 percent of the communication channel time.

The practicality of the proposed system will depend a great deal on the equipment simplicity and cost, as well as on accuracy. In this connection it is worth noting that almost all of the component parts of the proposed system are available today in low cost integrated circuit modules. For instance, relatively sophisticated precision phase lock loops and binary counters much longer than needed are available for under $5 each. The proposed system comprises parallel channels which are essentially identical. A realistic design goal is to have each channel cost under $50. The cost of the complete vehicle-mounted equipment should be about $300, excluding the communications transceivers. One could use the VHF or UHF transceivers already in the vehicle. Also note that the system's AM receivers could probably be simple either narrow-band, integrated-circuit RF amplifiers or another phase-lock loop. It is not advisable to use a superheterodyne receiver since in this case one would separately have to take account of frequency instabilities in the local oscillator. The entire system would be packaged on a card for easy addition to the anti-hijacking system.

B. System Errors

As long as each of the vehicle phase-lock loops remains locked to its respective AM carrier signals, the counters will provide valid information from which the vehicle position may be calculated. Multipath effects on one or more of the signals will occasionally cause position errors to appear;

however, these errors will be relatively small and will be bounded. Should any of the loops lose lock, very large errors will be generated and these errors will not be subsequently corrected except by some form of re-initialization.

The cause of a phase-lock loop losing lock or slipping cycles is due to the presence of noise along with the input signal. In general, a signal-to-noise ratio of + 6 dB is needed for the loop to acquire the signal. If modulation or transient phase error is present, a higher signal-to-noise ratio is needed to acquire and hold lock. The signal-to-noise ratio is related to the loop noise bandwidth. This bandwidth is subject to two conflicting requirements:

- The loop bandwidth must be narrow to minimize the external noise which enters the loop.
- The loop bandwidth must be wide to enable the loop to quickly acquire and track the signal.

To illustrate several of the loop design considerations, some preliminary estimates can be made of expected performance. If a carrier signal of 1 MHz is assumed, frequency variations due to transmitter instability should be no greater than about 0.1 Hz. Similarly, Doppler shifts due to vehicle motion should be less than 0.1 Hz. Frequency variations due to multipath are unknown, however, a reasonable estimate for a loop which could track the signal under all expected conditions would have a natural frequency of 10 Hz. Using this figure as a first estimate and assuming a critically dampened loop filter, a loop noise bandwidth of approximately 40 Hz would result.

The average noise power expected in a 40 Hz band at 1 MHz is approximately -110 dB M. The average signal power received from a 1 MHz, 50 kW transmitter at a distance of 100 miles is about -64 dBM. Of this power, approximately half, or -67 dBM is carrier (assuming 100% modulation). If the remaining -67 dBM were uniformly distributed as side-band energy over a 10 KHz bandwidth, approximately (-67 -27) -94 dBM will appear as interference in the 40 Hz bandwidth of the loop. If a receiver noise figure for the front end is 7 dB (antenna, cable, preselect filter, etc.); the noise at the loop input will be -110 + 7 = -103 dBM. The total noise plus interference at the loop input will be -93.5 dBM and the overall carrier-to-interference ratio at the loop input will be +26.5 dB.

Analysis* has shown that a signal-to-noise ratio of 10 dB would result in a mean time to unlock of 10^6 seconds for a first order loop with a 40 Hz bandwidth. This would be equivalent to less than one cycle slip per day in continuous operation. Operation at signal-to-noise levels greater than 20 dB, would make cycle slipping highly unlikely except in cases where the truck spent long periods of time in tunnels or other enclosed, well-shielded areas. For these cases, signposts could be positioned at key locations to automatically provide reinitialization to the counters. The signposts could also be located at terminals and other areas frequently passed by vehicles.

*Andrew Viterbi, "Principles of Coherent Communication", McGraw-Hill, 1966.

APPENDIX C: SIGNPOSTS

Signpost systems are generally classified as either passive or active. A passive system utilizes receivers at fixed locations to accept information transmitted from vehicles passing a signpost. The location information is then transmitted to the base station via telephone lines or on radio communication links. Each vehicle transmits its identification code. This code is coupled with the signpost location data and is relayed to the base station.

Two factors complicate the use of passive signposts. The first factor results from the situation when more than one vehicle transmitter is in the range of the signpost receiver. The receiver must be sufficiently sophisticated to distinguish each vehicle selectively and accurately. The second factor is related to the requirement for a communication network to relay signpost information to the base station. These factors have mitigated against the use of passive signpost systems except in special applications.

In an active signpost system, the wayside signpost devices transmit unique identification codes to passing vehicles for subsequent transmission by vehicles to the base station. Each vehicle is equipped with a receiver to accept the wayside post signal as the vehicle comes within range of the signpost. This signal is then decoded and the address of the wayside post placed in the vehicle's memory unit.

Other information can be recorded in the vehicle at the same time that location information is collected. This other information can be the odometer reading of the vehicle when passing the signpost or the time of

day. The signpost signal could also be used to re-initialize a supplementary dead reckoning or RF location system. In any event, the location information will be stored in the truck until it is interrogated by the base station or until the truck encounters an "alert" or "alarm" condition.

Methods for signalling between the vehicle and the signpost include electromagnetic radiation (in the form of radio waves, low-frequency induction or optical methods) or acoustic radiation. Acoustic devices tend to be larger and heavier than equivalent radio devices. Also, acoustic devices currently used for traffic sensing are high power and cannot be battery operated. For these reasons, installation would tend to be more expensive than the alternative radio transmission approaches. An additional consideration is that the use of acoustic devices in the vehicle would constitute a "mixing" of technologies, which would unduly complicate the system.

Low-frequency inductive loops are used extensively as vehicle detectors in traffic control systems. The common method of installation is to bury them in the roadbed, however, which makes them unsuitable for trucking company use. Optical methods have generally proven to be unreliable due to such environmental conditions as dirt, fog, ice, and snow. For the requirement of a trucking system, the installation and maintenance problems associated with establishing a signpost system make all approaches other than radio transmission impractical.

Among the factors which affect the design of a signpost device are: range of transmission, frequency of operation, power requirements,

modulation technique, data format and false alarm and dismissal rates. Each of these factors will be discussed briefly.

1. Range. The operating range of a signpost is governed by the receiver sensitivity, the required signal-to-noise ratio at the receiver, the allowable output power of the transmitter and such other factors as antenna gain, propagation medium, and noise improvement due to modulation techniques. In general, at a range of approximately 500 feet, a vehicle may receive the signal even when it merely passes several blocks from the intersection.

2. Frequency. In most cases, the signpost will be radiating at less than 0.10 watts and, therefore, will not require licensing. The frequency will depend upon the availability of equipment and components, on the ambient electromagnetic environment, and on the topographical features of the installation area. At the lower frequencies (e.g., citizens band - 27 MHz) a large selection of circuitry and components is available. The free-space attenuation also tends to be low at these frequencies. The average noise power in urban areas increases at low frequencies, however, and may require higher transmitter powers. Efficient antennas tend to become large at low frequencies as well.

At higher frequencies (e.g., 1000 MHz and above) highly efficient directional antennas can be used to avoid interference between adjacent signposts. Urban noise tends to be much lower at these frequencies. These advantages are offset by the high atmospheric attenuation in these bands and the high cost and relative inefficiencies of components and circuits which operate at UHF and above.

3. Power. The method used for powering the signposts will have very significant effects on the overall system cost. A battery powered device will require periodic battery changes but will have a simple and dependable power supply subsystem and will be inexpensive to install. A device which requires an external supply will be more expensive to install, since tie in with the local power companies is necessary. This factor also puts constraints on where the devices may be mounted. The advantage for this approach is that maintenance and service expense is minimized.

4. Modulation. The principal function of the signpost is to transmit the signpost ID (location in the form of a digital message. While any form of digital modulation could be used, binary noncoherent frequency shift keying (FSK) is most often used. This technique is easy to implement, has good error rejection characteristics, and can be used with threshold detectors to ensure that weak signals are ignored and only reliable messages based on strong signals are received.

5. Data Format. As a minimum, each message transmitted by the signpost must contain signpost ID and/or location. In addition the message may contain start and stop bits, synchronization codes, parity check bits, and error correction codes. The addition of ancillary data increases the reliability of transmission but at the cost of complexity and added expense.

6. False Alarm and False Dismissal. False alarm is the situation whereby a vehicle receiver recognizes noise or interference as a signpost signal when, in fact, the signal is not present.

False dismissal is the situation whereby a legitimate signal is present but is so weak in relation to noise and interference that the receiver does not detect it. A high threshold in a receiver will reduce false alarms but will also increase false dismissals. The threshold setting is a compromise which requires careful analysis of the transmission link characteristics. A reasonable (though arbitrary) requirement would be that, on the average, a vehicle should not encounter a message error more than once per month.

An example of a low-density signpost distribution is shown in Figure C-1. Signposts are placed at a density of approximately one signpost per square mile. The signposts are located at intersections of major thoroughfares in such a way as to maximize the probability that traffic through the area will pass signposts. While it is possible to traverse the area without passing at least one signpost, it would probably require numerous detours around major intersections. In general, a truck driving at random through the area on major streets would pass a signpost once every two miles. If the truck were making deliveries to side streets in the area, the maximum distance between signposts would be four or five miles.

The minimum required transmitted power for a signpost is a function of frequency, required receiver signal-to-noise ratio, range, and distance between signposts. For a simplified "first cut" analysis, the configuration shown in Figure C-2 can be assumed to represent the signpost arrangement.

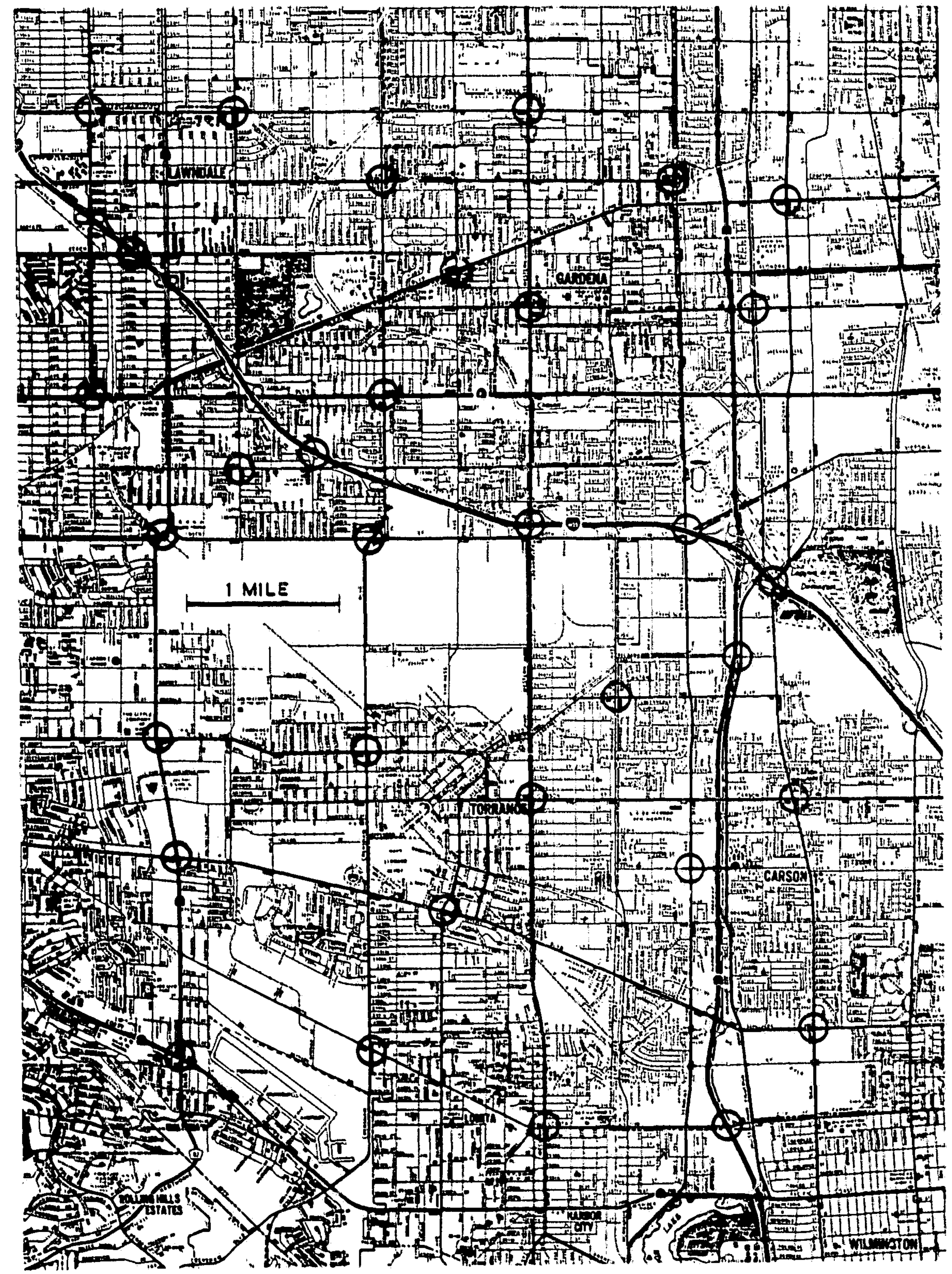

Figure C-1. Low-Density Signpost Distribution

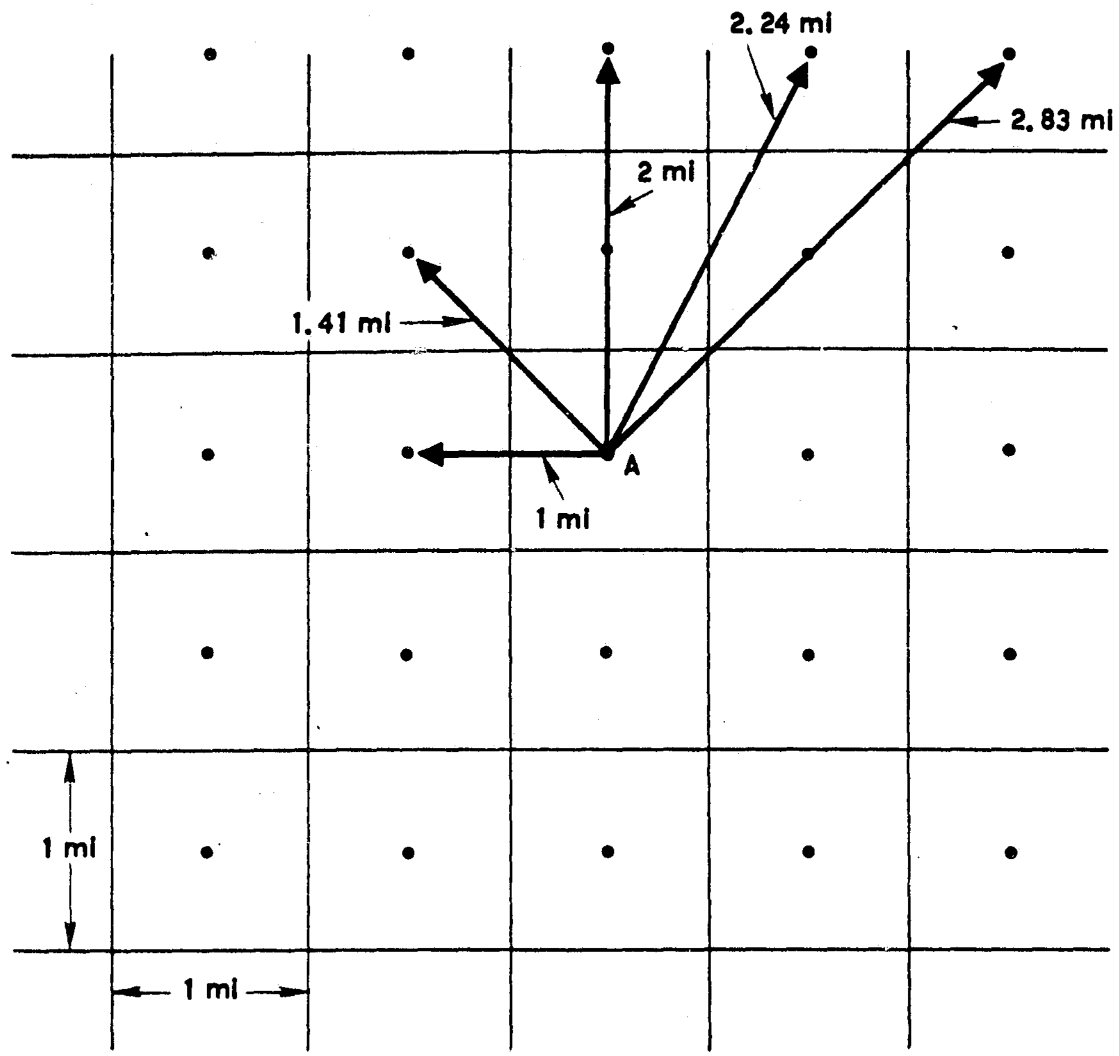

Figure C-2. Simplified Signpost Configuration

From signpost "A" there are four signposts at a distance of 1 mile, four at a distance of 1.4 miles, four at a distance of 2 miles, eight at a distance of 2.24 miles, four at a distance of 2.83 miles, etc. Each of these other signposts can be expected to contribute an interfering signal to a receiver in the vicinity of signpost "A". If the transmitter frequency is 150 MHz, the free-space path attenuation from these other signposts (assuming isotropic antennas) would be:

Distance	Attenuation
1.0 Mi.	80 dB or 10^{-8}
1.41 Mi.	84 dB or 4×10^{-8}
2.0 Mi.	87 dB or 2×10^{-9}
2.24 Mi.	88 dB or 1.67×10^{-9}
2.83 Mi.	89.5 dB or 1.1×10^{-9}

if signposts at distances of 3 miles or more are ignored. If the receiver bandwidth is 10 KHz, the ambient noise level in an urban area at 150 MHz will be 2×10^{-10} milliwatts. The effective noise interference will be the sum of the ambient noise plus the interfering signals from nearby signposts. If the effective transmitted power from a signpost is P_t, the total interference in the vicinity of any particular signpost will be:

$$2 \times 10^{-10} + (4 \times 10^{-8} + 4 \times 4 \times 10^{-9} + 4 \times 2 \times 10^{-9} + 8 \times 1.67 \times 10^{-9} + 4 \times 1.1 \times 10^{-9}) P_t \text{ or } 2 \times 10^{-10} + (8.18 \times 10^{-8} P_t \text{ milliwatts}$$

If signposts at distances of up to 5 miles are included the interference becomes:

$$2 \times 10^{-10} + (11.58 \times 10^{-8}) P_t$$

At distances of several miles in urban areas, the path attenuation values for free spaces conditions become unrealistic. The figures do illustrate some of the system design considerations however, and an overall interference function of

$$2 \times 10^{-10} + (12 \times 10^{-8}) P_t$$

will be used as a reasonable approximation. This function is shown graphically in Figure C-3. The graph shows the total interference power increasing linearly with transmitter power when the signpost power is greater than -20 dBm. For power levels below -30 dBm, the ambient noise becomes the predominant factor.

The long dashed lines in Figure C-3 represent the received signal power (for an isotrophic antenna) at distances of 100 feet, 500 feet and 1500 feet from the signpost. At distances greater than about 1500 feet from the signpost, the signal is below the interference level. At a distance of 500 feet, the signal is generally about 10 dB above the interference level. At 100 feet, the signal is about 24 dB above the interference level. A detailed analysis of the communication performance of the short range link between the signpost transmitter and the vehicle will yield optimum threshold levels for the receiver to minimize false receptions. The short dashed line is indicative of a threshold 20 dB above the interference level. For this setting the vehicle would not accept signpost information until it came within approximately 200 feet of the transmitter.

It should be noted that, in the region of interest, the range of the system appears independent of the transmitter power (i.e., both the signal power and the interference power increase linearly with signpost transmitter power). In actuality, the receiver sensitivity will set a lower limit on transmitter power. For example, if the receiver sensitivity is -50 dBm and a 20 dB threshold is required, the transmitter power will have to be at least 0 dBm. The range of the transmitter will be about 200 feet and will not increase even if the transmitter power is increased.

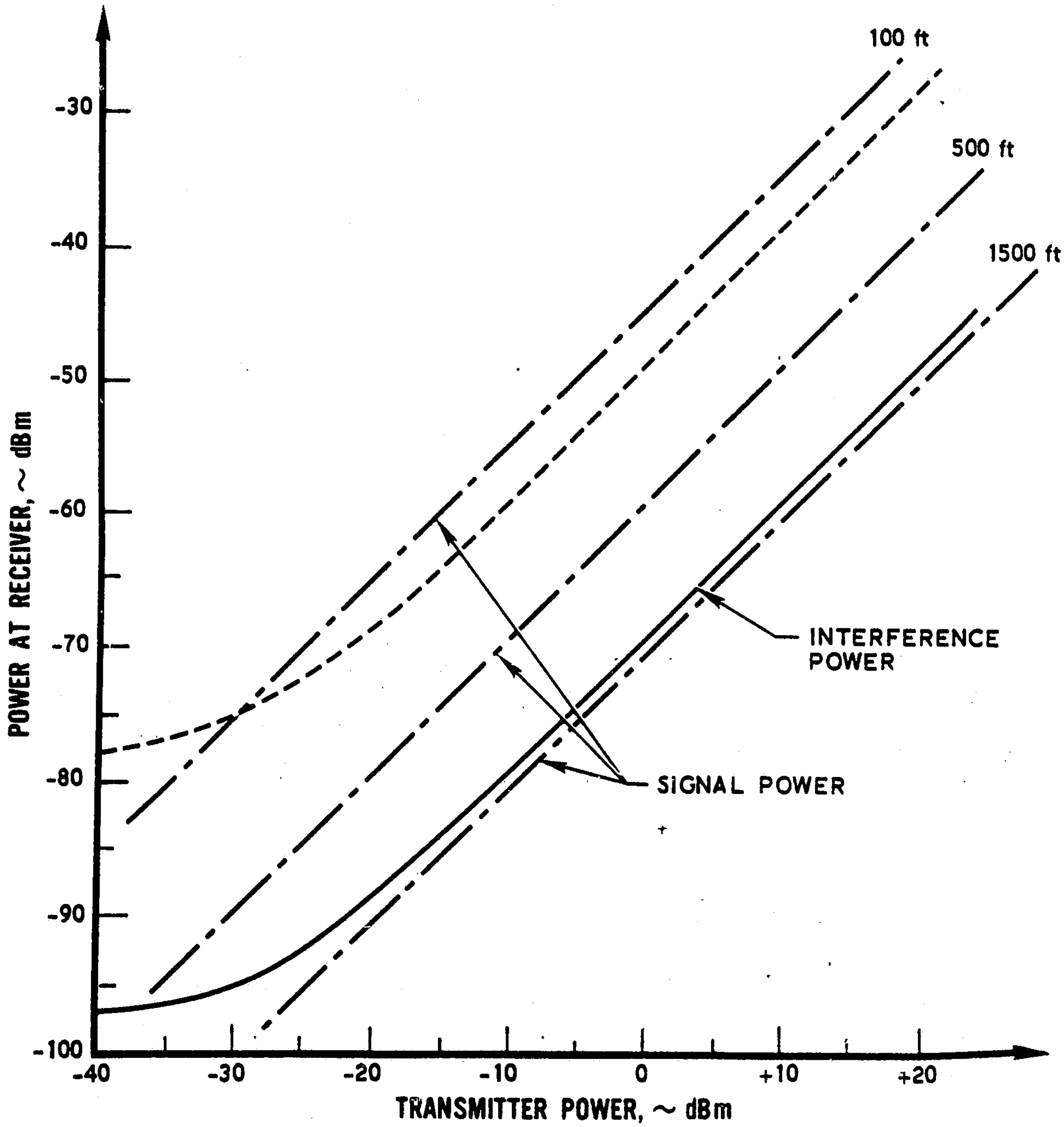

Figure C-3. Plot of Signal and Noise Power at Receiver as a Function of Transmitter Power

APPENDIX D: DEAD RECKONING

A. Conventional Dead Reckoning

The dead-reckoning system is autonomous in that it employs equipment installed on the truck for determining location rather than depending on externally provided equipment. Examples of instruments used for dead-reckoning are a magnetic compass and an odometer. This approach is differentiated from an alternative dead-reckoning system, which transmits raw sensor data back to a base station where it is integrated and processed to obtain position fixes. This system has the advantage in that the base station processor makes use of city street maps to fit the vehicle path to the street pattern. Major drawbacks to this approach are the expense involved with having a sophisticated computer at the base station and the requirement for having a considerable amount of data transfer. In order to maintain a continuous track on a vehicle, sensor data should be relayed back to the base station at least once each second. If each vehicle transmission required a 50-bit message to include a preamble, vehicle ID, and parity checks as well as the sensor data, there would be a contribution of about 50 bits per second from each truck. The average trucking company shares a mobile radio channel between 20 to 30 trucks. If all the trucks were using the location equipment the channel would have to handle 1,000 to 1,500 bits per second of data transfer. Requirements for message protocol or polling procedures would also increase channel usage. Such usage would be impossible for trucking fleets.

This technique is suitable for situations where the user can dedicate a radio channel to carry digital data exclusively. The only users in this category are those who qualify for priority channel assignments by being in the military or public safety areas.

The candidate dead reckoning systems investigated in this report are as follows:

- Rate Gyro/Odometer
- Compass/Odometer
- Compass/Dual Odometer
- Compass/Rate Gyro/Odometer

All candidate systems employ instruments that provide information on the direction of travel (heading) and the distance traveled. The instruments provide an electrical readout which is fed to a simple computing circuit. This circuit computes the truck location in X, Y coordinates. This information is then available for transmission to the central station at specific time intervals or on request.

1. Error Sources. Typically, accuracy and cost are mutually opposing goals because more accurate equipment is usually more expensive. Judicious selection of components and system configuration can, however, frequently lead to optimum performance, (i.e., least cost for the accuracy required). Thus the purpose of this study is to evaluate the potential accuracy of the candidate systems through an error analysis. The error analysis is conducted by first determining the influence of the component errors on the system location accuracy. The component error sources

in turn form the basis for the study. These errors sources are discussed briefly in the following section.

a. Magnetic Compass Errors. The major source of error in measuring the direction of travel is distortion of the magnetic field. The instrument errors due to the compass itself are typically small. The magnetic field of the earth contains local anomalies caused by various sources such as power plants and metal objects, like a passing car. These distortions are taken into account in the error analysis. Both the magnitude of the magnetic distortion and the correlation coefficient are considered.

The correlation is utilized to describe the relationship of field distortion between one point and another. Another source of compass error correlation can, for the most part, be adjusted.

b. Odometer Errors. The major error source in measuring distance traveled with an odometer is variation in tire conditions. Acceleration and braking cause relative motion between the tires and the road. Variations in tire pressure, speed, and the crown in the road also affect accuracy. The single largest source of error seems to be a slippery road condition, such as encountered during a rain storm. Errors contributed by the odometer itself appear to be quite small. An odometer distance measuring unit was installed and evaluated in the Aerospace feasibility demonstration system during FY 73. The characteristics and performance of this unit was considered satisfactory for use in an operational system as well as in the demonstration system. The odometer unit will utilize an electronic wheel actuator mechanically designed with standard SAE fittings so that it would interface with standard truck odometer drives. The wheel actuator will be

connected to an electronic counter to accumulate the pulses from the wheel actuator. Appropriate gear ratios and calibration procedures will be used to provide a ratio of 1 count per foot of truck motion.

Data from numerous test runs made by the demonstration vehicle were analyzed and statistical inferences were made. Repeatability of the odometer readings were found to be extremely good: results from a series of 18 mile runs yielded a standard deviation from the mean of 65 feet. These values represent less than 0.07percent random error (one sigma). The systematic errors were found to be somewhat larger. The test runs revealed that the mean difference between odometer readings and measurements from the map used in the base station was 995 feet or 1.0 percent. It is probable that lane changes and freeway access roads, not accounted for on the map, were major contributors to the positive bias of the readings. This bias could be eliminated by marking the map with distance traveled figures obtained from actual measurements. The measurements would be made for specified route segments. The dispatcher would simply add the separate segments to determine the current vehicle position. The location within a particular segment would be determined using a planimeter directly with the map starting from the beginning of the segment. The use of low density signposts would also be effective in keeping systematic errors within bounds.

The only significant instrument consideration is quantization, i.e., the smallest measurable change in distance. Strictly speaking, there are both random and systematic error sources contributing to distance-traveled

errors. The largest error source is the systematic error than can be modeled as an error in scale factor. A scale factor error contributes to location error that is proportional to distance traveled, while a random error only contributes an error that is proportional to the square root of distance. For simplicity in analysis, all the distance-traveled errors were lumped into the scale-factor error. A conservative number of 0.3 percent was assumed for the standard deviation of this error.

c. Rate Gyro Errors. A rate gyro provides a measurement of change in direction of travel rather than the actual direction of travel (heading angle) at an instant in time. The rate gyro measurements can be integrated (or summed at frequent but discrete time points) over a period of time. This integrated signal is the change in heading angle during the time period. The heading angle can then be computed by adding the computed heading angle change to the actual heading angle at the beginning of the time period. An estimate of the initial heading angle is used if the precise angle is not known.

The error model of an inexpensive rate gyro is complicated by the effects of nonlinearities. There are also errors in the scale factor and changes in the bias. Where possible, known error sources are assumed to be eliminated by compensation in the computation circuit. In this study all the residual error sources were lumped together and represented as a as a single random error source. This random error is assumed to contribute an error with a standard deviation of 0.08 degrees when integrated (or summed) over a period of 0.5 seconds. This value of 0.16 degrees per

second is considered to be a conservative estimate of the errors that will be experienced.

d. Dual Odometer Errors. A dual odometer operates by separately measuring the rotation of two wheels. The distance traveled is computed by averaging the two measurements. The change in heading angle is determined by differencing the two wheel measurements. The accuracy in the distance traveled can be expected to be the same as for a single odometer. Accordingly, for the standard deviation of the distance-traveled measurement error, a value of 0.3 percent is used in this study as discussed for the single odometer.

The error in the measurement of change in heading angle will depend on the difference in the tire conditions for the two wheels. Variations in the crown in the road, pressure of the tires, wind direction, truck load distribution and wheel slip will introduce errors. For this study, all the errors in measuring change in heading angle were lumped into a single random error source. It was assumed that the error in measuring the difference between the distances traveled of each wheel was 0.4 percent of the average distance traveled. Further, it was assumed that the errors were independent when sampled every 30 feet. Thus, when traveling at 40 mph and sampling every one-half second (every 30 feet) the standard deviation of the error is 0.12 feet. This leads to a heading angle error of 1.5 degrees in 30 feet, i.e., 3.0 degrees per second when traveling 40 mph.

e. Computational Errors. Current available computing circuits should be quite adequate so that computational errors will introduce

negligible effect on the location error. The speed of available circuits is also sufficient to permit the computation cycle to be short enough to overcome any possible sampling frequency difficulties, even at the fastest truck speed.

2. Summary of Results. The basic configurations studied can be portioned into two generic groups. The configurations in the first group are as follows:

- Rate Gyro/Odometer
- Compass/Odometer

In these configurations there are only two measurements available, one heading angle or change in heading angle measurement and a distance-traveled measurement.

The rate gyro measures heading-angle rate of change and, accordingly, exhibits a drift in computed heading angle. The rate gyro is, however, much more accurate than such other sensors as the dual odometer or a steering wheel sensor.

The magnetic compass differs from the rate gyro in that it measures the heading angle rather than change in heading angle. The magnetic compass does not exhibit the drift in heading angle as do the dual odometer and the rate gyro. Because of this drift characteristic the error analysis indicates that the compass/odometer system performs much better than the rate gyro/odometer system.

The configurations in the second group are as:

- Compass/Dual Odometer
- Compass/Rate Gyro/Odometer

In these configurations three measurements are available; i.e., heading angle, change in heading angle, and distance traveled. The two measurements concerned with heading angle must be combined to provide a single estimate of the angle. An algorithm for combining these measurements is established before the error analysis is conducted. The exhibit heading-angle error depends on how the two measurements are combined. The distance traveled error, on the other hand, will be the same for these configurations as for configurations of the other group. The error analysis indicates that the compass/rate gyro/odometer system is superior to the compass/dual odometer system simply because the rate gyro error is much less than the change-in-angle error, as measured by a dual odometer.

This summary of results is simplified by concentrating on the two strongest candidates; i.e., one from each of the two generic groups. In addition, the discussion is limited to a single route configuration. For this route the truck is traveling at 40 mph in a straight line. The dead-reckoning system does not use the fact that the route is fixed and the computing circuit updates the location estimate every 30 feet (every 0.5 seconds in this case). The straight line route is chosen because any other route selection will tend to decrease the location error for the same distance traveled. Also, at a fixed speed an error correlated in time is equivalent to an error correlated

in distance (space). Thus at fixed speed and direction no distinction need be made between time and distance correlations.

a. Compass/Odometer System. The compass error model used for the error analysis was a two-parameter model. The two parameters are the standard deviation of the errors and the correlation coefficient. With standard deviation of error assumed to be 10 degrees, the compass measurement would exhibit errors in excess of 10 degrees over 35 percent of the time. If the correlation coefficient is assumed to be virtually zero, then the swings in the measurements would be very fast since the errors are independent in time.

For the case where the errors are uncorrelated, the contribution to the location error due to the compass errors can be computed from the following formula.

$$\sigma_{xy} = \sigma_\theta \sqrt{S \cdot \Delta S} \quad \text{(D-1)}$$

where

σ_{xy} = location error standard deviation

σ_θ = compass error standard deviation

S = distance traveled

ΔS = distance traveled per computation cycle

The location error for a system with an error-free odometer can be computed using this formula. The location errors along the route are as follows:

Actual Distance Traveled	Location Error Standard Deviation
2 Miles	98 Feet
20 Miles	311 Feet
40 Miles	439 Feet

The contribution to the location error due to an odometer error with a standard deviation 0.3 percent are listed below.

Actual Distance Traveled	Location Error Standard Deviation
2 Miles	32 Feet
20 Miles	316 Feet
40 Miles	634 Feet

The total location error as a result of the error contributions from both the compass and the odometer can be obtained from these two tables.

The total location error is computed by combining the two error effects by using the root sum square method, which produces the following results:

Actual Distance Traveled	Total Location Error Standard Deviation
2 Miles	103 Feet
20 Miles	443 Feet
40 Miles	771 Feet

Thus, even with the conservative value for the error-source standard deviation, this candidate system offers excellent accuracy because the large swing in compass errors is averaged out.

The compass error can be expected to be correlated. Due to correlation, the speed of swing due to the errors is not as violent as without the correlation assumed for the previous computation. The true nature of the error correlation as experienced in an urban environment is not currently known. To show the influence of correlation, however, the previous computations will be repeated with a correlation coefficient of 0.7. The formula for location error can be modified to account for correlated errors as follows:

$$\sigma_{xy} = \sigma_\theta \sqrt{S \cdot \Delta S} \left(\frac{1 + \rho}{1 - \rho} \right)^{1/2} \qquad \text{(D-2)}$$

where ρ = compass error correlation coefficient and the other symbols are as in equation 1. Equation (D-2) is, in general, an approximation but is quite accurate in this particular case.

Using equation (D-2) the contribution to the location error due to the correlated compass error is as follows:

Actual Distance Traveled	Location Error Standard Deviation
2 Miles	233 Feet
20 Miles	740 Feet
40 Miles	1045 Feet

As before, the contribution to the location error due to odometer errors can be added using the root mean square method. The total location error, taking into account the combined effect of the two instruments, is as follows:

Actual Distance Traveled	Total Location Error Standard Deviation
2 Miles	235 Feet
20 Miles	804 Feet
40 Miles	1222 Feet

The correlation of compass errors obviously has a significant effect. The ultimate acceptability of this system seems to hinge on the specific type of compass errors that are exhibited in a urban environment.

b. Compass/Rate Gyro/Odometer System. The advantage of including a rate gyro in the dead-reckoning system is that it provides the opportunity to decrease the heading angle error without significantly increasing the system cost. The compass measurement and the rate gyro measurement are combined in the computing circuit to provide an estimate of the current heading angle. As mentioned before, the magnitude of both the error in estimated heading angle and the error in location are effected by the choice of algorithm used to combine the compass and rate gyro measurements.

As a starting point a recursive, filtering, algorithm was used. The equation for this algorithm is simply

$$\hat{\theta}_n = a\theta_n^* + (1-a)(\Delta\theta_n^* + \hat{\theta}_{n-1}) \qquad \text{(D-3)}$$

where

$\hat{\theta}_n$ = heading angle estimate at time t_n

$\hat{\theta}_{n-1}$ = heading angle estimate at time t_{n-1}

θ^*_n = compass measurement at time t_n

$\Delta\theta^*_n$ = rate gyro measurement integrated over time period t_{n-1} to t_n.

a = filter gain.

In using this algorithm the filter gain, a, was selected to minimize the error in estimated heading angle. For this criteria, it can be shown that the estimated heading angle error can be computed with the aid of the following equation.

$$\sigma_{\tilde{\theta}} = \sqrt{\sigma_\theta \sigma_{\Delta\theta}} \qquad \text{(D-4)}$$

where

$\sigma_{\tilde{\theta}}$ = estimated heading angle error standard deviation

σ_θ = compass error standard deviation

$\sigma_{\Delta\theta}$ = rate gyro error standard deviation

This is, in general, an approximation but is quite accurate for this specific problem.

The addition of a rate gyro significantly reduces the estimated heading-angle error. Starting with a compass-error standard deviation of 10 degrees and then adding a 0.08-degree per cycle rate gyro to the system reduces the standard deviation of the heading angle error to 0.9 degrees.

However, the magnitude of the location error is not reduced, in fact, it is increased.

The addition of the rate gyro increases the location error because the resulting heading angle estimation errors are highly correlated. Note first that in the preceding calculations the compass errors are uncorrelated. Also the algorithm of equation (D-3) is optimal for minimum heading-angle error but it is not optimal for minimum location error. In effect, the magnitude of the location error is effected by magnitude of the sum of the heading errors, not the sum of the magnitude of the heading errors. It is this phenomenon that must be taken into account when improving performance.

The algorithm of equation (D-3) must be modified before the location errors for a system with the addition of a rate gyro can be properly evaluated. The study to date has shown that the addition of a rate gyro can provide improved accuracy when an alternate algorithm is used. However, the degree of improvement has not yet been determined. Note that so far the discussion has been limited to a compass with virtually uncorrelated measurement errors.

In the study to date, the problem of using a rate gyro to reduce the effects of correlation in compass errors has not been addressed. Another algorithm for combining compass and rate gyro measurements is required if the compass errors are significantly correlated. Although it may be that another simple recursive filtering algorithm will make an otherwise unacceptable system perform within tolerance, this cannot be determined with assurance until an error analysis is performed for that case.

c. <u>Simulation Results.</u> A simple computer program has been developed to simulate the error characteristics of the dead-reckoning system. A Monte Carlo simulation is employed to propagate the errors that would be encountered when a number of different trucks followed the same route. Sample results are shown in Figures D-1 through D-4. For this simulation the speed of each truck is 40 mph. There are eight trucks following a straight-line route.

The distance traveled errors for this sample run are zero. The compass heading errors are uncorrelated ($\rho = 0$) and standard deviation is 10 degrees (certainly a conservative number). The location errors along the route are as follows:

Actual Distance Traveled	Location Error Standard Deviation
2 Miles	124 Feet
20 Miles	210 Feet
40 Miles	447 Feet

The location error including an odometer distance errors of 0.3 percent can be readily added to the simulation results by the root sum square method. With the odometer errors included the total location errors are as follows:

Actual Distance Traveled	Total Location Error Standard Deviation
2 Miles	128 Feet
20 Miles	380 Feet
40 Miles	775 Feet

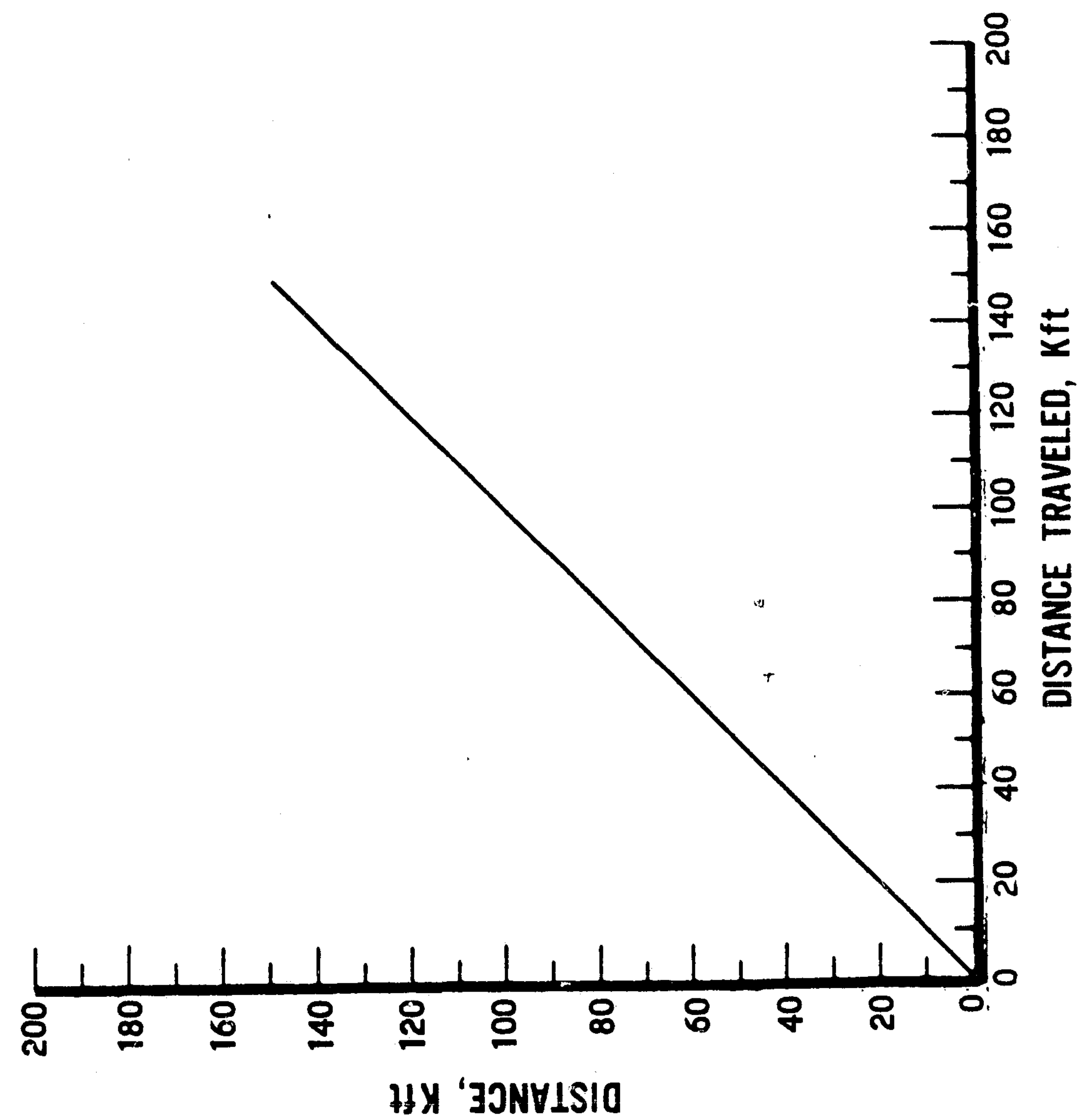

Figure D-1. Map of Truck Route Used for Simulation. Distance is measured in feet (40 miles total) and the truck speed is 40 mph.

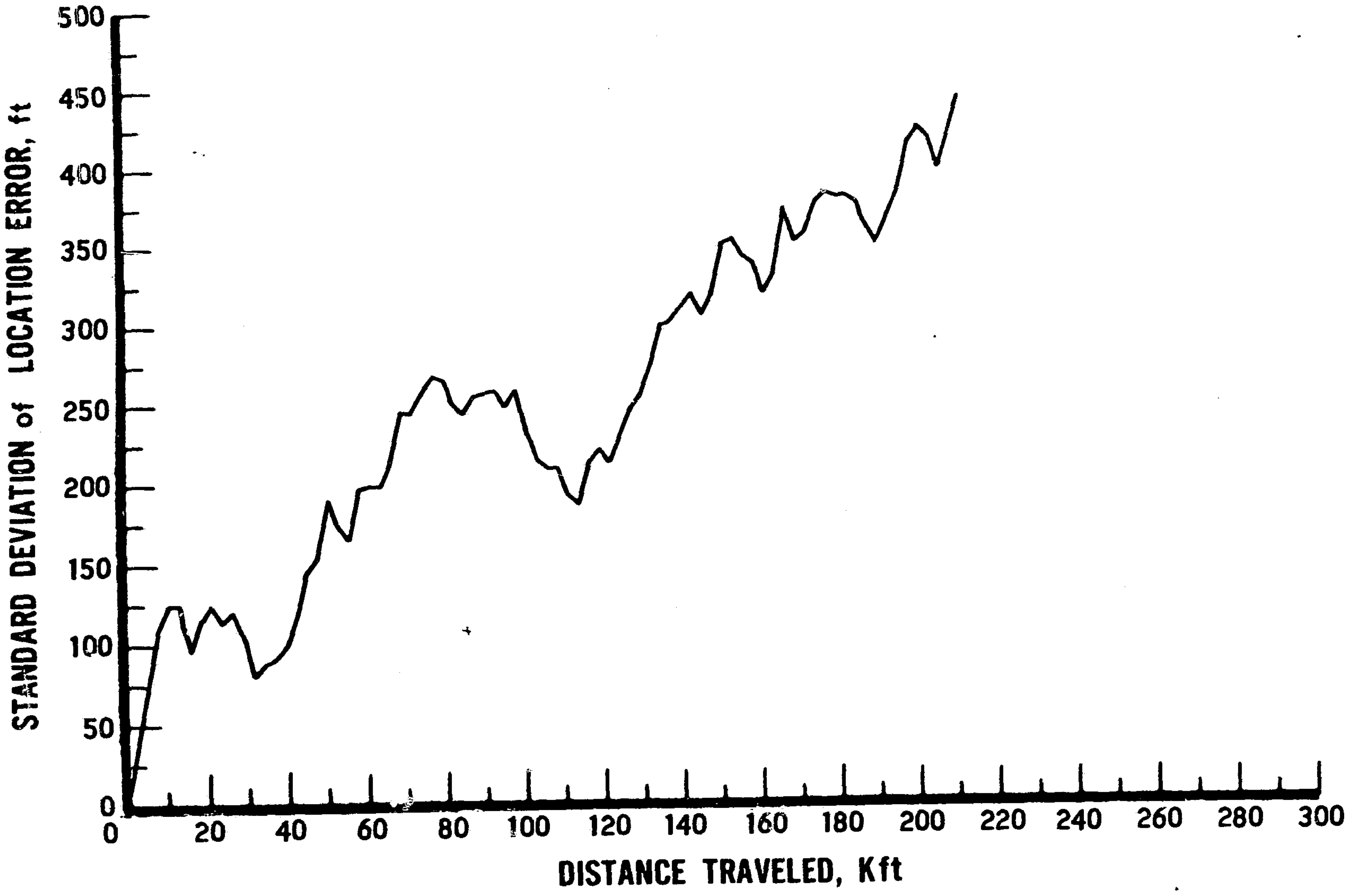

Figure D-2. Standard Deviation of Location Error as a Function of Distance. Standard deviation and distance traveled are both indicated in feet. Standard deviation is computed through root sum square of the location errors of each truck.

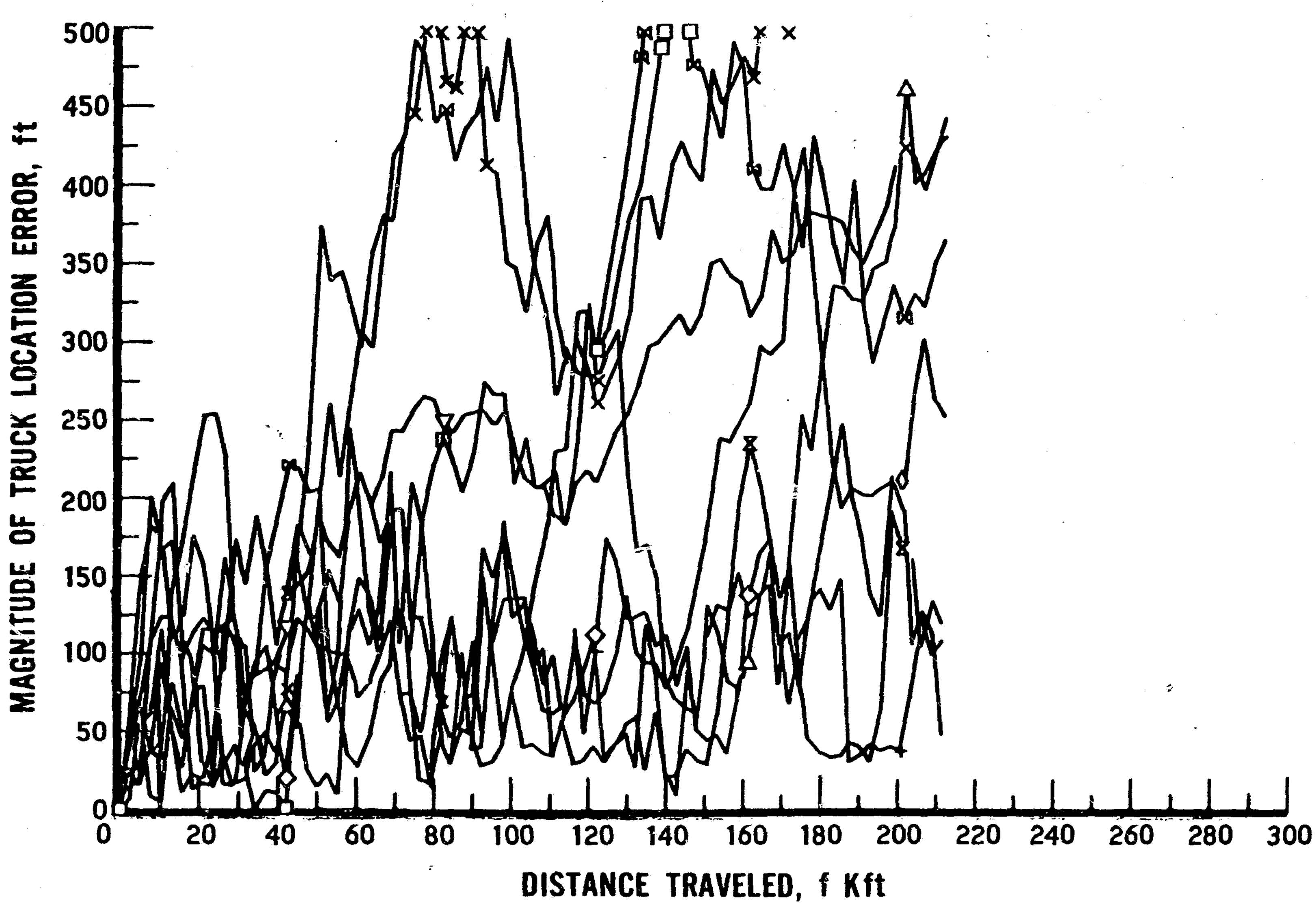

Figure D-3. Magnitude of Truck Location Errors as of Function of Distance. Magnitude of error and distance are in feet. Each curve traces the magnitude of the location error for a truck as a function of distance traveled.

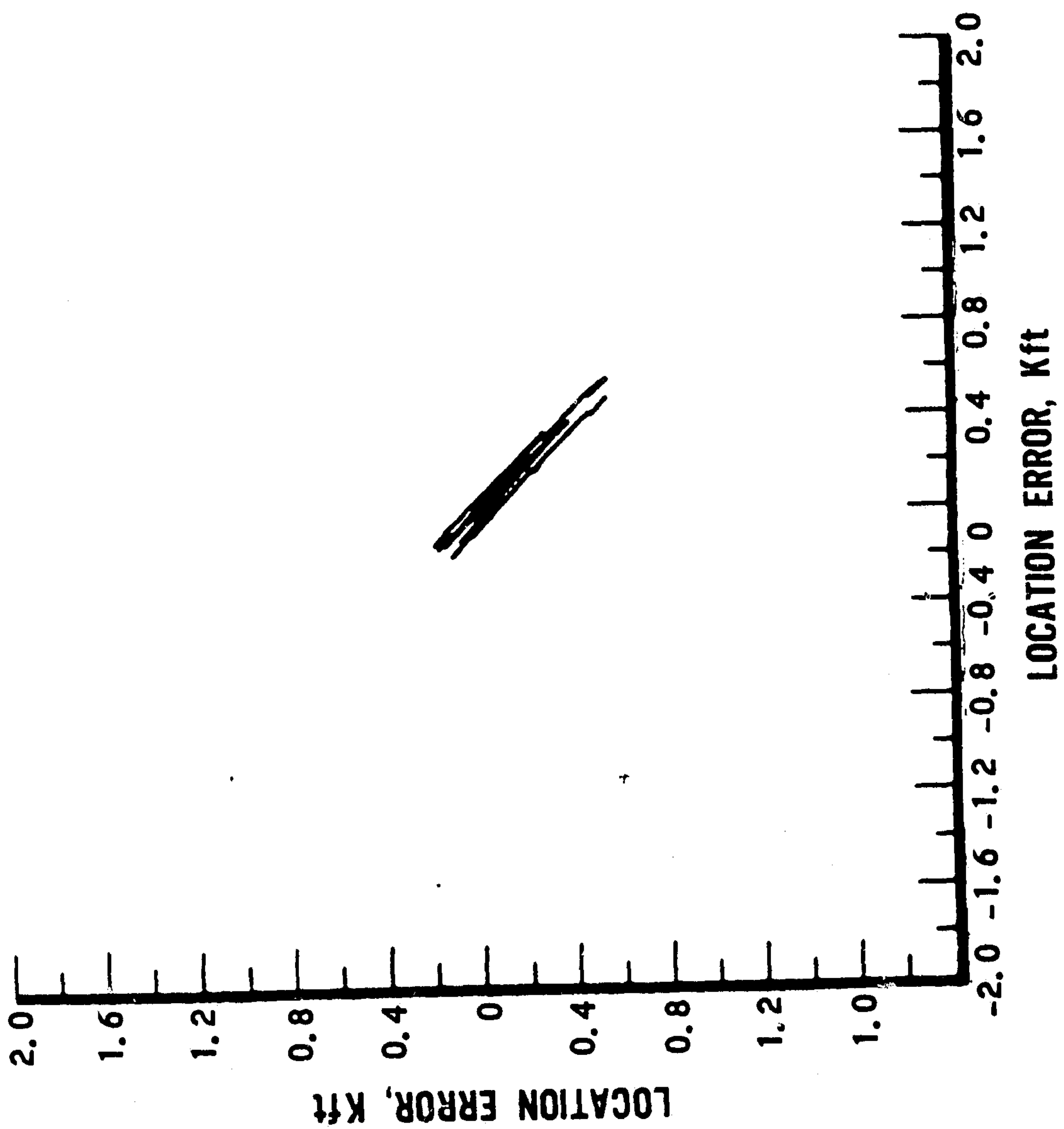

Figure D-4. Components of Truck Location Errors. The X and Y components of the location error for each truck (measured in feet) are traced and superimposed on this one composite plot.

The sample results shown in Figure D-2 are not in precise agreement with the analysis because this simulation utilizes only eight trucks. A simulation employing many more trucks would conform more precisely to the analytical results. Simulation results do confirm that the systems studied are feasible provided the error sources, as modeled, are correct.

B. Hybrid Dead Reckoning

Hybrid dead reckoning refers to truck location using instruments contained within the truck supplemented by occasional calibration of the instruments using low density supports. The basic instruments under consideration are an odometer and a compass in conjunction with support transmitters.

The cost of implementing a hybrid dead-reckoning system is potentially low with respect to the truckborne instrumentation, and the overall cost is dependent upon the net signpost transmitter cost. The latter cost is related to the accuracy of dead reckoning; i.e., truck location accuracy between signpost updates. High accuracy of dead reckoning implies low signpost density and lower signpost cost.

An analysis was performed to develop a relationship between maximum signpost separation and the relevant error parameters. This relationship is as follows:

$$S \leq \frac{\sigma_T^{\,2}}{2\sigma_\theta^{\,2} S_c}$$

where: S is the maximum signpost separation, σ_T is the allowable standard deviation of the location error, σ_θ is the standard deviation of the heading error and S_c is the correlation distance constant for the heading sensor.

The maximum signpost separation is shown in Figure D-5 as a function of compass error for several values of compass-error correlation distance. In each case the allowable standard deviation of the location error is held to 300 feet. The figure indicates that if the compass error was 6 degrees and, if the error correlation distance were 100 feet, a truck would have to pass a signpost at least once every 8 miles in order to keep the location error within 300 feet.

The computer simulation (as described) was performing using a compass error of 10 degrees. This simulation indicated that a 300-foot location error could be maintained with a signpost separation of up to 15 miles. This result was due to the fact that the simulation assumed an uncorrelated compass error.

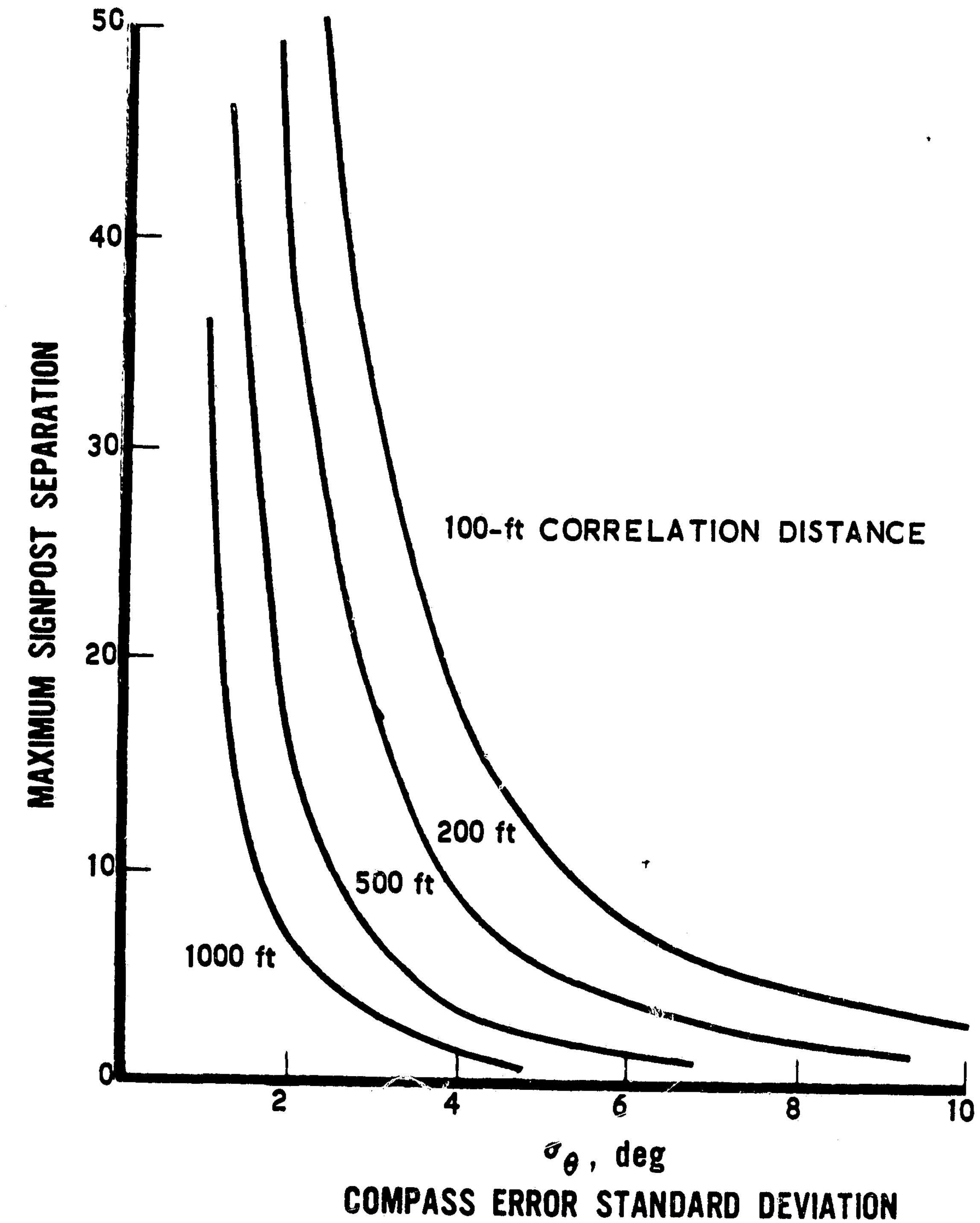

Figure D-5. Maximum Support Separation for 300-foot Location Error

END