

A Systems Engineering Approach to the Design
of a Vehicle Navigation System

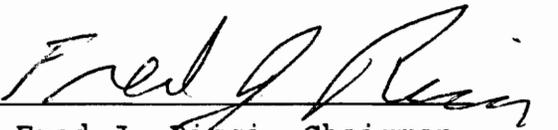
By

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(ABSTRACT)

With continuing advances in technology, the market for vehicle navigation systems is expected to grow over the next several years. The systems engineering process is applied to ensure that an effective system is developed. After the need is established, four methods of implementing a vehicle navigation system are described. A system employing differential GPS to determine the location of the vehicle is chosen to be the most feasible approach.

Based on this choice, the operational requirements and maintenance concept are defined. Possible design approaches are then discussed. A terrestrial radio link is selected over a satellite link to transmit the differential corrections to users. Finally, an analysis is performed to estimate the number of reference stations that will be required to implement the system. The results can be used as a guideline

to determine the potential cost of providing a differential GPS service.

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Introduction

Science, from its outset, has continually addressed questions concerning man's purpose and place in the universe. Over the course of time, significant progress has been made in answering at least one of these questions. Determining one's location is a basic problem for which solutions are continually evolving.

The navigation of the oceans by early explorers required the use of the stars. Celestial navigation, however, is not very accurate and depends on very precise measurements. It can also only be done at night when the sky is clear enough. Even modern systems, employing the latest in electronic technology, are not extremely accurate and have their individual drawbacks.

Another area of travel that utilizes the benefits derived from technological advances is air transportation. A large amount of electronic equipment both in the air and on the ground is required for monitoring the position of planes and other air traffic to ensure safety. For many years, ground transportation has relied on less precise means of navigation. Most people depend solely on maps, signs, and landmarks to determine their current location and decide how to get to a desired destination. Only in recent years have people been able to realize the benefits of a vehicle navigation system.

The design of a vehicle navigation system is a large undertaking that cannot be completely covered in this paper. The objective is to provide a systems engineering approach to the design of the system. The systems engineering process is sequential, iterative, and "directly concerned with the transition from requirements identification to a fully defined system configuration ready for production and consumer use" (Blanchard, p. 34). Since the process is continuous, the complete application is beyond the scope of this paper. The paper does, however, attempt to show how systems engineering is applied to ensure that an effective system is developed.

Section 1.0 covers the definition of need. Before the design of a system begins, an absolute need for the system should be established. The need might result from an existing deficiency or the lack of a certain capability. The need should be well defined so that time and money are not expended on a system that is not really required. Once the need has been established, different technical approaches are considered. This feasibility analysis is covered in section 2.0. There are several methods of implementing a vehicle navigation system. In this section, four approaches are described and the advantages and disadvantages associated with each of them are discussed.

Section 3.0 defines the operational requirements for the system. These requirements are derived from an evaluation of

the need and the feasibility of the different approaches. The operational concept covers a variety of topics. For instance, the objective of the system is defined along with the expected use of the system. Performance parameters, physical parameters, and effectiveness factors are described in both qualitative and quantitative terms. In addition, the expected deployment and distribution of the vehicle navigation system is discussed.

The operational requirements lead to the development of the maintenance concept, which is covered in section 4.0. The maintenance concept describes the overall support environment for the system. The anticipated levels of support for the system, throughout its life-cycle, need to be defined early in the design process. The goal is to establish a baseline from which specific support requirements can be derived at a later time.

The conceptual design for the vehicle navigation system is developed in section 5.0. The purpose of this section is to determine how the system requirements can be met by various technical alternatives. First, the possible design approaches for realizing the in-vehicle portion of the navigation system are described. Next, the required communication link is discussed. In this case, there are two main alternatives for implementing the communication link that is needed. The alternatives are evaluated and the best one is chosen. Based

on this choice, a possible design approach is demonstrated. The results can be used to evaluate the effectiveness of the system. The design approach provides a basis for comparison against other possible designs.

Finally, section 6.0 performs an abbreviated functional analysis of the vehicle navigation system. The analysis is accomplished using both operational and maintenance functional flow diagrams. The diagrams describe the overall system by structuring requirements.

1.0 Definition of Need

1.1 Navigation Systems

The current pace of technological change has generated consumer demand for products that enable tasks to be performed with greater speed and simplicity. This demand is most evident today in the area of information. Facsimile machines and cellular phones have improved communications, providing an individual or company the ability to compete in a global marketplace. People have become accustomed to the quickness, ease, and convenience associated with these devices. In fact, the fax and cellular phone have become a part of everyday life.

Similarly, people have a desire to reach a given destination with minimal time and effort. For the commercial vehicle sector, this means a savings of money. However, the use of a navigation system by rescue units (ambulance, police, fire) can possibly save lives. A navigation system can increase productivity for a delivery company, or for people whose job requires them to spend time on the road, by reducing travel time. The Federal Highway Administration (FHWA) estimated in 1985 that "approximately 6% of all driving in the U.S. is due to incorrect choice of route" (Rillings, p. 34). Today, the FHWA estimates this value to be around 15% (McCosh,

p. 27).

There are additional potential benefits to vehicle navigation systems. For instance, reducing the amount of time that people spend on the road reduces the amount of traffic and pollution. A reduction in congestion means that the potential for accidents is decreased, and accidents are a major contributor to traffic problems. Also, there are benefits offered by vehicle navigation systems that are more difficult to measure such as the added comfort that a driver feels knowing that he or she is almost guaranteed not to get lost. This knowledge will result in less stress on drivers.

Navigation systems have had the largest impact on the Japanese market due to the need and demand. Most city streets in Japan have no names, and the Japanese are "willing to try any new electronic gadget" (Cross, p. 34). The systems sold in Japan are part of an overall entertainment system that offers weather information, quizzes, and color television. Some Americans believe that this is the main reason the systems are purchased (Brooke, p. 78). A vehicle navigation system will not sell as quickly in the United States based on these merits alone.

In-car navigation systems, however, have appealed to auto engineers for many years. For example, "as far back as July 1966, we described details of MMD, a moving map display that projected 35-mm film reels" (Simanaitis, p. 67). Until now,

the technology required to make the system effective was too expensive. Another factor that supports the future appeal for vehicle navigation systems is that nearly "every automaker has included an electronic navigation device in its concept car of the future" (Vizard, p. 107). An effective system needs to be developed in the United States to gain consumer support.

1.2 Currently Available Vehicle Navigation System

1.2.1 Description

In order to understand the problems associated with the current vehicle navigation system available in the United States, an explanation of how the system operates is first required. The system is manufactured by Blaupunkt Bosch Telecom, a division of the Robert Bosch Corporation, and is called the Travelpilot. The Travelpilot uses a navigation technique known as "dead reckoning" combined with computerized map matching to determine the location of the vehicle. The location is shown on a moving-map display. The maps are on CD-ROM disks supplied by Etak Inc., and there are currently five regional maps available. The display is a four and one-half inch video screen, and the position of the car is marked by an arrow-shaped cursor. Instead of the cursor moving with the car, the map scrolls and rotates below the cursor. The

map rotates such that the driver sees the roads as they would appear through the windshield. In other words, the top of the screen does not always refer to north due to the changing orientation of the map. This configuration is optimal for the driver, since the driver should not have to stare at the screen for an extended period of time to obtain information on where to go.

The destination is marked on the display by a star. It is selected by the user and can be specified as a street, a street address, an intersection of two streets, or a city. The initial position of the car must also be specified by the user. The display provides the driver with information such as the "airline" distance to the destination, the direction to the destination, and the compass direction. The display has nine map scales that range from one-eighth of a mile per inch up to 30 miles per inch.

As previously stated, the Travelpilot uses dead reckoning and map matching to determine position. Dead reckoning is the process of calculating present position using the knowledge of initial position and estimates of the distance and direction traveled. The Travelpilot measures the distance and direction based on information from sensors attached to the non-drive wheels of the car. The left and right wheel sensors detect when the outside wheel has traveled farther than the inside wheel through the difference in their readings. This

information is used to determine direction based on the distance and the angle turned. The Travelpilot also uses an electronic fluxgate compass to provide directional data. This compass is usually mounted on the rear window of the car. The inputs from these devices are used to compute an apparent ground path.

Based on the information provided by the wheel sensors and the compass, complex computer algorithms compare the vehicle's movements with the applicable map. This map matching is a form of artificial intelligence. The navigation computer and CD-ROM drive are combined as one unit that can be mounted in the vehicle in any convenient location. The car's position is continually updated through this process, as long as the car stays on the map. Dead reckoning is used to keep track of the vehicle's position when it turns onto a road or parking lot that is not in the map database, until it returns onto the map. Figure 1.2.1-1 illustrates the process used by the Travelpilot to determine position (Simanaitis, p. 68). Figure 1.2.1-2 shows an overview of the system architecture (Brooke, p. 78).

The design of the Travelpilot offers several benefits. For instance, the system is self-contained, requiring no radio transmitters, satellites, or other infrastructure. It is a completely stand-alone system. In addition, it is relatively inexpensive, selling for about \$2495 not including

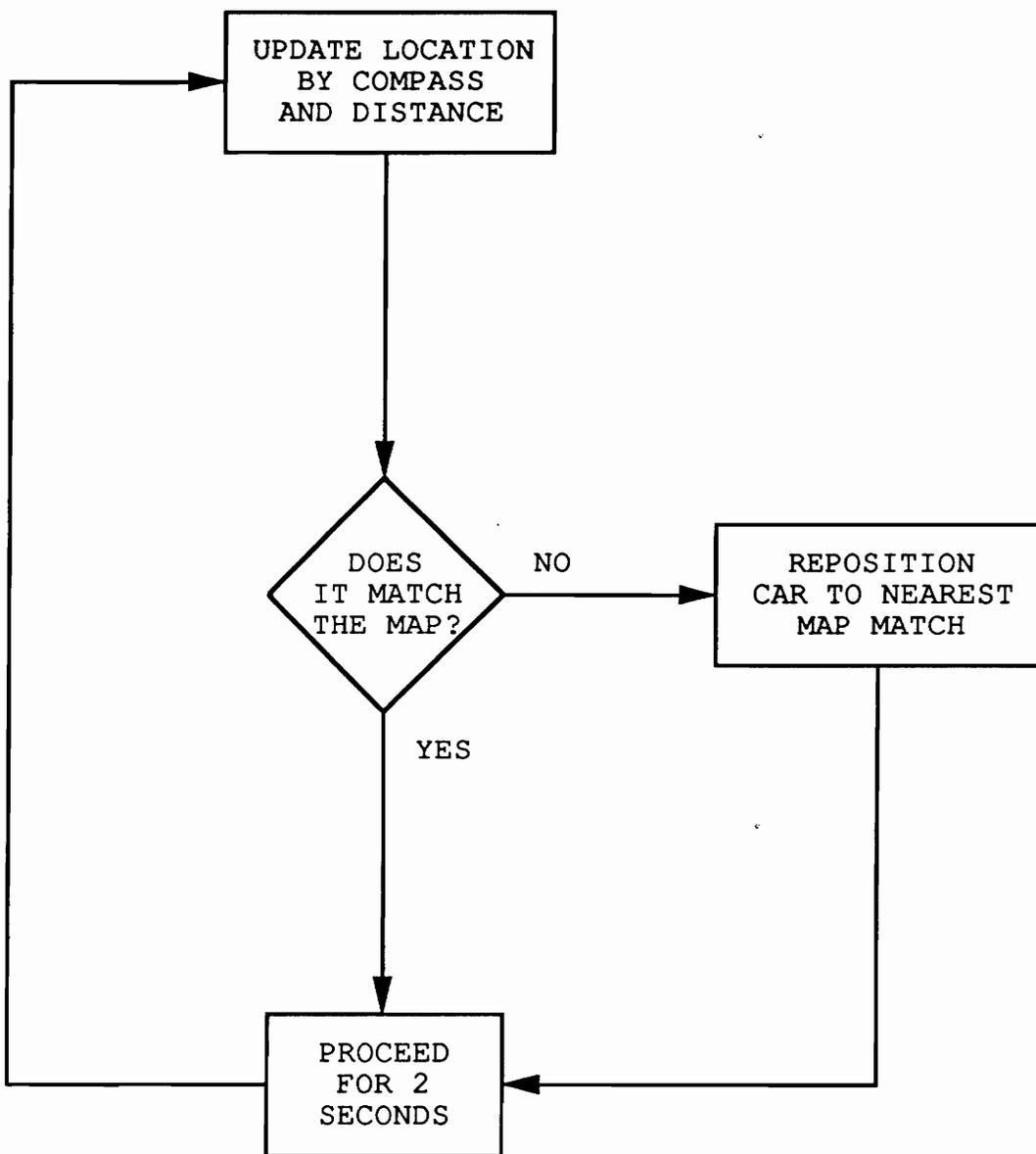


Figure 1.2.1-1. Process used by Travelpilot.

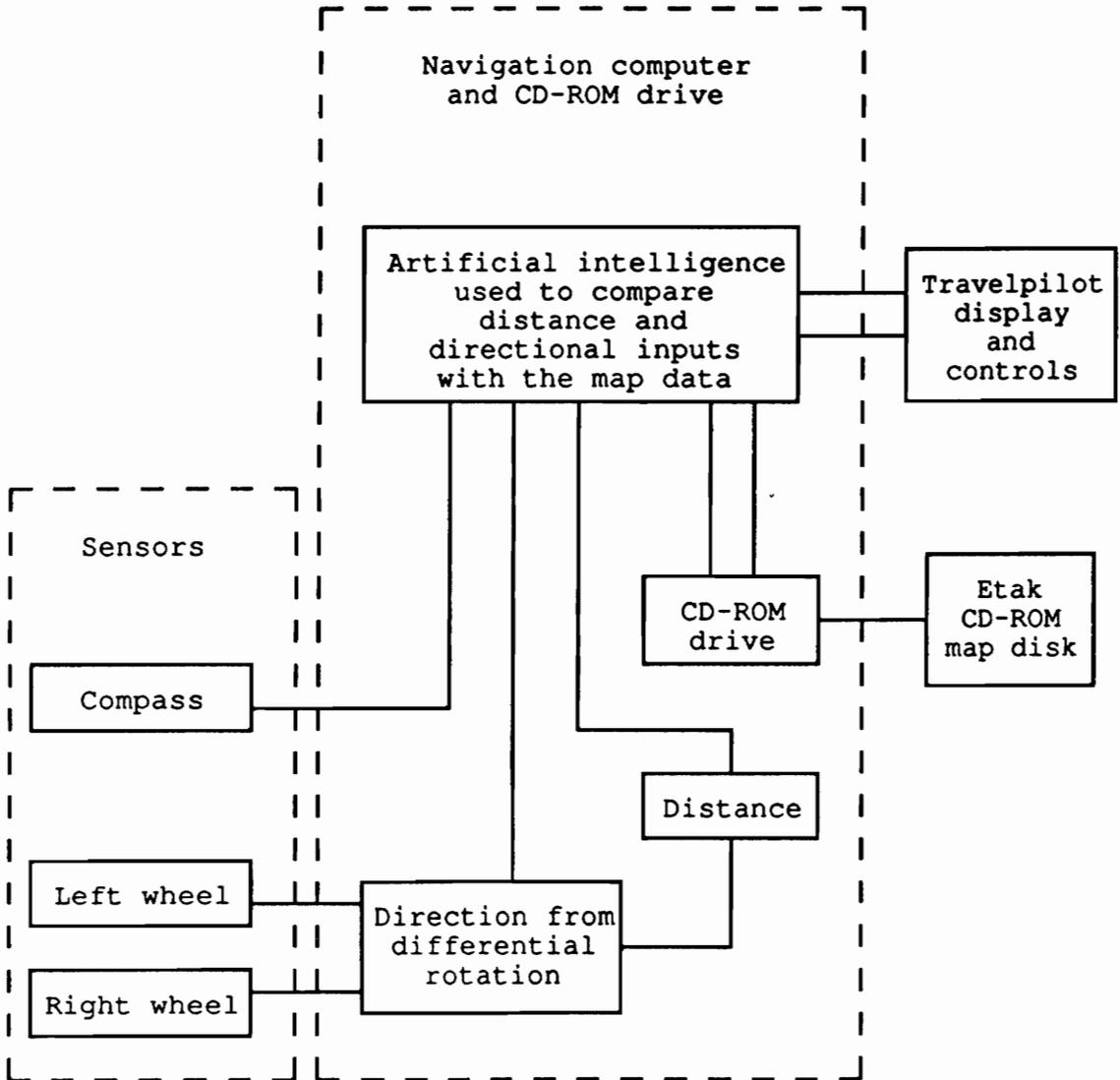


Figure 1.2.1-2. Travelpilot system architecture.

installation. Installation raises the price closer to \$3000. Another benefit is that the navigation system can be installed as an after-market option. In other words, the system is not factory installed.

1.2.2 Deficiencies

Despite these advantages offered by the Travelpilot through its method of determining position, there are several deficiencies associated with the design. An important point to make at this time is that a meaningful measure of accuracy cannot be obtained for this type of system. The only real measure is in terms of reliability. In other words, how often does the vehicle get tracked incorrectly? This is referred to as the loss rate. Although the loss rate for an area like greater Los Angeles is estimated at once in a thousand miles, the rate is highly dependent upon the environment in which the navigation system is used (Buxton, p. 43).

One source of error in determining the current position is derived from the equipment itself. For example, magnetic interference caused by steel structures, railroad tracks, or even the activation of rear-window defoggers can disorder the geomagnetic compass. The compass is typically mounted on the rear window "away from the engine's dense metallic and electrical interference" to reduce effects like these

(Simanaitis, p. 68). The geomagnetism combined with dead reckoning results in an average error of approximately 5%, which increases as the car travels ("Mazda...", p. 28).

The wheel sensors can also cause problems. When dead reckoning systems are used on vehicles that commonly travel at high speeds, such as ambulances, the high heat that is generated can melt the wheel sensors. The sensors will also degrade in this manner on cars over time. A navigation system, especially when used in life-and-death situations, must be dependable. Another problem with the sensors is that they must be installed on the non-drive wheels of the car. Therefore, this system cannot be supported by a four-wheel drive vehicle. Spinning wheels will cause errors in the measurements. These errors will accumulate at a rapid rate.

Computerized map matching is another source of error in determining the correct position of the vehicle. For instance, positioning errors can result when the vehicle enters an uncharted area. An uncharted area is one that is not present in the map database. The navigation computer might choose a nearby street that is on the digital map by mistake. If this occurs, the location of the car must be inputted again. The location can also be adjusted using a manual correction feature on the display that moves the car one street to the left or to the right. Another instance in which the vehicle would have to be repositioned is if it

travels aboard a ferryboat. According to the Travelpilot, the vehicle will have remained in the same place even though it will have actually traveled a potentially large distance. Although errors such as these can be corrected, they are costly in terms of time and inconvenience to the driver. Most of the user operations on the Travelpilot are disabled over speeds of 2 mph for safety reasons. Therefore, the driver would most likely have to stop the vehicle to correct problems.

A final source of error in determining the correct position of the vehicle is the failure of the Travelpilot to accurately account for changes in elevation. An inclinometer is offered by Blaupunkt, but only as an option. This device can cost an extra \$200 or more (Wiggins). The inclinometer functions as another sensor, providing data to the navigation computer when changes in elevation are detected. Without this device, positioning errors can accumulate when the navigation computer attempts to correlate the changes in distance with the digital map, since the map is flat on the screen and does not account for actual distance due to elevation changes. A very hilly area that contains many nearby streets might cause problems for the system.

1.3 Need For New Navigation System

The preceding examples show why the development of a more dependable and accurate vehicle navigation system is desired. There is a definite need for an improved system for consumers. Dead reckoning is one of the oldest and most basic of navigation techniques. Some people believe that it "might be nothing more than an interim solution to car navigation" (Vizard, p. 109).

A new vehicle navigation system needs to be available in the United States by the year 2000. The Japanese automakers have already taken advantage of the market in Japan and are expected to introduce a system in the U.S. when they have a well-proven design. Currently, the Japanese do not sell systems in this country due to cost, demand, and system capability (Sawyer, p. 61). These factors, however, are expected to improve over the next several years due to advances in technology.

2.0 Feasibility Analysis

In the previous section, the need for an improved vehicle navigation system was established. The design of the system can be accomplished through several different technical approaches. These approaches focus on the method for determining the location of the vehicle. The possible approaches include using the Global Positioning System (GPS), GPS combined with Russia's Global Navigation Satellite System (GLONASS), an inertial system, or differential GPS.

2.1 GPS Architecture

One method of determining the location of a vehicle is to use the Global Positioning System, dead reckoning, and map matching. GPS is a satellite-based positioning system developed by the Department of Defense. An open-use policy for the system was announced by President Reagan in 1983 following the downing of Korean Airlines 007. A user's position is determined based on signals received from the satellites. For a user on land, only three satellites are required since the position is in two dimensions. A more detailed explanation of how GPS works is given in the Appendix.

Using GPS, a vehicle's location can be calculated to a

position accuracy of 100 meters or less, with a probability of 95%. This is the accuracy level provided by the Standard Positioning Service (SPS), which is available to civilian users of the system. Authorized users, such as the military and official government users, are able to obtain much greater accuracy using the Precise Positioning Service (PPS). The level of SPS accuracy is controlled by invoking an operational mode known as Selective Availability (SA). This capability was developed for security reasons and intentionally degrades the accuracy provided by the signals. The Department of Defense wants to prevent hostile forces from obtaining precise positioning information because it believes that the timing and accuracy could be used to target missiles ("Europeans..., p. 60). SA was first used on March 25, 1990.

The ability of the U.S. military to degrade the accuracy provided by GPS is only one concern over using the system. Another concern is that the U.S. military might pull the system from service during national emergencies. A user must be able to depend on the availability of the system. A similar concern is that users need to be informed of system failures, such as the transmission of an unhealthy satellite signal, in a timely manner. The Defense Department has stated that "system malfunction alerts will be transmitted within 2 hr.", but this time period is unacceptable ("Europeans..., p. 60). This time period can actually vary anywhere from two to

six hours depending on how soon the problem is detected (Alsip, p. 2). It appears that no action has been taken to ensure that users are notified quickly. The new navigation system must have reasonable integrity.

Although a navigation system utilizing GPS technology is more accurate than a basic dead reckoning system, there can be problems associated with it. For instance, signal loss can be caused by tunnels, tall buildings, or a close grouping of trees. As a result, positioning errors will occur. Under these conditions, the vehicle will rely completely upon the map matching and dead reckoning for position updates. These functions essentially act as a back-up to GPS. GPS does, however, alleviate the driver from having to reinput the location of the vehicle if a mistake is made. It should also be noted that there are no user fees associated with GPS.

The additional hardware required to implement this type of system includes a GPS receiver and an antenna. The software in the navigation computer must also be modified to incorporate the use of positioning information from the satellites. Although GPS is not yet fully operational, the full constellation of 24 satellites is expected to be usable by the end of this year. Currently, only 22 satellites are operational, and another was just recently launched.

The market for vehicle navigation systems using GPS technology has not been tested in the United States, but the

Japanese have encountered moderate success. In fact, a few "writers have predicted that by 1993 every car produced in Japan will have a GPS-based navigation system built into it", and the market growth by 1995 is estimated to vary between \$1.5 billion and \$4.0 billion (Barnard, p. 102). The problems associated with GPS, however, might prevent this from happening. The demand has been growing for the development of a navigation system that is more accurate ("Mazda...", p. 28).

2.2 Combined GPS/GLONASS Architecture

Another approach to consider in the design of a vehicle navigation system is the use of positioning information from both the GPS and GLONASS satellite systems. Russia's GLONASS system is very similar to GPS, which makes it possible to design a receiver that can use signals from each. Most of the research in this area has centered around the use of these combined receivers for aviation. Honeywell, Magnavox, and MIT Lincoln Laboratory are in the process of developing such receivers.

A navigation system using a combined GPS/GLONASS receiver for positioning information offers several advantages over a system using only GPS. For instance, the concern over the integrity of the system would be alleviated. GLONASS will consist of a total of 24 satellites, and there will always be

enough satellites in range to provide redundant signals that can be used to determine which satellite signals are unsatisfactory (Klass, p. 57). An unsatisfactory, or unhealthy, signal is caused by the degradation of an atomic clock aboard the particular satellite. In addition, the increased number of available satellites will result in better coverage. The two systems have been found to have complementary coverage (Nordwall, pp. 71-72). As with GPS, access has been offered to civil users of the GLONASS system by Soviet officials into the next century. The satellites are expected to continue meeting performance standards for 15 years (Hughes, p. 38).

A vehicle navigation system using a GPS/GLONASS receiver would still use dead reckoning and map matching as a back-up. Although a measure of accuracy cannot be found for a combined receiver, the achievable accuracy should not be much better than that provided by the GLONASS system. The GLONASS system has a specified accuracy of 40 meters (Nordwall, p. 72). Therefore, this system would be more accurate than one using only GPS. This higher level of accuracy is due to the fact that "Soviet authorities have stated that the Glonass signal will not be artificially degraded" (Nordwall, p. 72).

Despite these benefits offered by a dual receiver, there are a few major concerns over using this type of system. For example, the GLONASS system is not scheduled to be fully

operational until 1995. With the current conditions of instability in Russia, there is a good chance this completion date will not be met. In addition, James Danaher of the 3S Navigation Corporation in LaGuna Hills, California stated that "Glonass signals could experience interference from the proposed Low Earth Orbit (LEO) satellites authorized at the recent WARC-92 international conference" (Klass(2), p. 55). (WARC stands for the World Administrative Radio Conference). The uplink transmission frequency for the LEO satellites is in the 1.6 GHz band, which is adjacent to the L-band carrier frequency of 1602.5625 MHz used by GLONASS. Although the idea of using a GPS/GLONASS receiver is feasible, further development and testing is required before the system can be implemented.

2.3 Inertial Navigation Architecture

Nissan has developed a new inertial vehicle navigation system that uses an optical-fiber gyroscope and a series of roadside beacons combined with dead reckoning and map matching to determine position. The optical-fiber gyroscope is 130 mm in diameter and uses 100 meters of 0.3 mm optical fiber. It measures angular velocities by calculating the time difference between light traveling clockwise in the circular optical fiber path versus counterclockwise. The time differences

correspond to frequency shifts and can be translated into rates of angular motion. The gyro is not affected by shock in the horizontal plane, so it is impervious to bumpy roads.

The roadside beacons are used to transmit information to vehicles such as the names of nearby intersections and their coordinates, the destinations of roads leading from the intersections, and distances from some central point. The beacons even transmit their own locations to aid in vehicle navigation. A frequency of 2.5 GHz is used by all of the beacons to digitally broadcast the signals. The signals are kept weak in order to prevent interference from different beacons. Due to the deliberate weakness of the signals, they can only be received in an area that is about 35 meters before and after the beacon, in a strip that is approximately 15 meters wide. These beacons are already being set up along major highways in Japan. Currently, they are being installed in the Tokyo, Osaka, and Nagoya areas, but the number is planned to increase over the coming years.

The main advantage of this system is that it provides a high level of accuracy. Nissan states that their system is able to determine the location of a vehicle to within five meters ("IVHS...", p. 1). This level of accuracy far exceeds that provided by a navigation system using only dead reckoning and map matching. There are, however, several disadvantages. For example, the system requires a large investment in

infrastructure. The attractiveness of the system to consumers needs to be determined at an early stage to justify the investment in infrastructure. Each beacon is estimated to cost around \$1000, and Japan plans to use 40,000 of them in a nationwide network (Brooke, p. 79). This results in a cost of approximately \$40 million. Based on these figures, this type of system would probably not be practical in the United States due to cost. The U.S. is about twenty times the size of Japan. Another disadvantage is that this system does not appear to be an after-market option. It is currently provided as an option on Nissan's Cedric, Gloria, and Cima models for the Japanese market. Most consumers will probably not be willing to buy a new car in order to obtain a navigation system.

2.4 Differential GPS Architecture

Another approach to designing a vehicle navigation system is to use differential GPS (DGPS) to calculate position. As with the GPS architecture, dead reckoning and map matching are used as a back-up when signal loss occurs. DGPS improves accuracy by using a reference receiver at a surveyed location. Since the position of the reference receiver is known, the receiver is able to determine the correction factors for the errors in each satellite ranging measurement that it receives.

These corrections are then broadcast real-time to the GPS receivers of users in the local area, which are able to apply them in their calculations to obtain a much more accurate position estimate.

A navigation system using this technique offers many advantages. The main advantage is the achievable accuracy. Differential GPS can provide accuracies of 10 meters or less. In other words, DGPS solves the SA problem associated with the use of GPS. The level of accuracy is affected by the distance between the reference receiver and the user. Another advantage is that the reference receiver can continuously monitor the integrity of the system. The receiver can warn users not to use a particular satellite signal if the signal is deemed unhealthy. As previously stated, an unhealthy GPS signal can normally be transmitting for two to six hours before users are notified, or the situation is corrected. This is an important benefit of DGPS since system integrity is a major concern. Finally, differential GPS does not pose a security problem due to the limited area for which the corrections are available and valid.

The fact that DGPS only functions in a limited area is also a disadvantage. Accuracy decreases as the distance between the user and the reference receiver increases. As a result, the system will require a certain number of reference receivers depending on the desired accuracy for the users.

DGPS relies on an infrastructure that will vary in cost based on the number of reference receivers that are needed. The users, however, will still be able to use the GPS signals and achieve 100-meter accuracy until the receivers are operational.

2.5 Life-cycle Cost

The life-cycle cost of each of the four approaches needs to be considered to determine if the methods are economically feasible. The costs encountered through the life cycle of each resulting system fall into three main categories that are shown in Figure 2.5-1. This cost breakdown structure (CBS) defines the categories as research and development, production, and operations and maintenance. These categories are further broken down to a level necessary to provide a reasonable evaluation.

Based on this allocation, the life-cycle cost of each system can be calculated by estimating the costs in each category for each year in the life cycle. A five year life cycle is used. These costs are discounted to the present value using a 10 percent interest factor. The results of this analysis for each different approach are shown in Table 2.5-1 through Table 2.5-4.

For the research and development costs, the assumption is

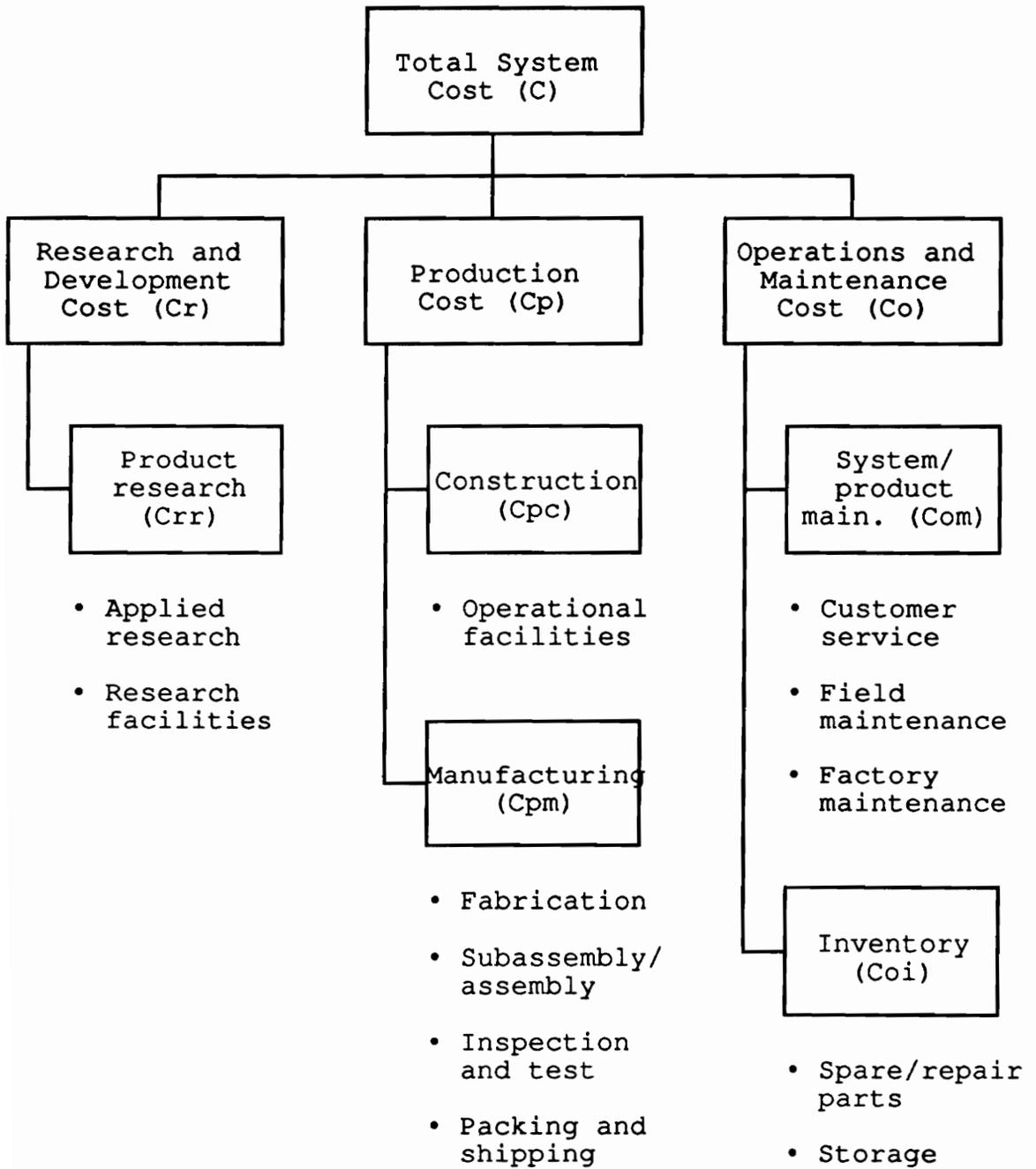


Figure 2.5-1. Cost breakdown structure.

Table 2.5-1. GPS architecture cost allocation by program year.

Activity	0	1	2	3	4	5	Total cost (million \$)
Research & Develop.	0.1	--	--	--	--	--	0.1
Production							
Construction	--	--	--	--	--	--	--
Manufacturing	--	10.0	14.0	20.0	24.0	24.0	92.0
Operations & Main.							
Product Main.	--	1.0	1.4	2.0	2.4	2.4	9.2
Inventory	--	0.25	0.35	0.5	0.6	0.6	2.3
Total actual cost	0.1	11.25	15.75	22.5	27.0	27.0	103.6
P/F, 10, n	1	0.9091	0.8265	0.7513	0.6830	0.6209	
Total present cost	0.1	10.227	13.017	16.904	18.441	16.764	75.454

Table 2.5-2. Combined GPS/GLONASS architecture cost allocation by program year.

Activity	0	1	2	3	4	5	Total cost (million \$)
Research & Develop.	5.0	--	--	--	--	--	5.0
Production							
Construction	--	--	--	--	--	--	--
Manufacturing	--	10.5	14.7	21.0	25.2	25.2	96.6
Operations & Main.							
Product Main.	--	1.25	1.75	2.5	3.0	3.0	11.5
Inventory	--	0.25	0.35	0.5	0.6	0.6	2.3
Total actual cost	5.0	12.0	16.8	24.0	28.8	28.8	115.4
P/F, 10, n	1	0.9091	0.8265	0.7513	0.6830	0.6209	
Total present cost	5.0	10.909	13.885	18.031	19.670	17.882	85.378

Table 2.5-3. Inertial navigation architecture cost allocation
by program year.

Activity	0	1	2	3	4	5	Total cost (million \$)
Research & Develop.	0.15	--	--	--	--	--	0.15
Production							
Construction	40.0	20.0	20.0	20.0	10.0	10.0	120.0
Manufacturing	--	7.5	10.5	15.0	18.0	18.0	69.0
Operations & Main.							
Product Main.	--	1.75	2.45	3.5	4.2	4.2	16.1
Inventory	--	0.15	0.21	0.3	0.36	0.36	1.38
Total actual cost	40.15	29.4	33.16	38.8	32.56	32.56	206.63
P/F, 10, n	1	0.9091	0.8265	0.7513	0.6830	0.6209	
Total present cost	40.15	26.728	27.407	29.150	22.238	20.217	165.890

Table 2.5-4. Differential GPS architecture cost allocation by program year.

Activity	0	1	2	3	4	5	Total cost (million \$)
Research & Develop.	0.1	--	--	--	--	--	0.1
Production							
Construction	15.0	10.0	5.0	3.0	1.0	--	34.0
Manufacturing	--	10.0	14.0	20.0	24.0	24.0	92.0
Operations & Main.							
Product Main.	--	1.0	1.4	2.0	2.4	2.4	9.2
Inventory	--	0.25	0.35	0.5	0.6	0.6	2.3
Total actual cost	15.1	21.25	20.75	25.5	28.0	27.0	137.6
P/F, 10, n	1	0.9091	0.8265	0.7513	0.6830	0.6209	
Total present cost	15.1	19.318	17.150	19.158	19.124	16.764	106.615

made that all of these costs are incurred in year zero. The GPS, inertial navigation, and differential GPS architectures require minimal costs as compared to the GPS/GLONASS architecture since they are proven designs. Currently, a combined GPS/GLONASS receiver is not available. The development of this receiver will require considerable time and effort.

The production costs are broken down into two categories, construction and manufacturing. Construction costs are the costs associated with building the operational facilities that are needed to support the operation of the system throughout its life cycle. These costs only pertain to the inertial navigation and differential GPS architectures, which require some level of infrastructure to function. For the inertial system, each roadside beacon is estimated to cost around \$1000. The system will require about 40,000 beacons to initially establish an effective operational capability. This amount is reflected in Table 2.5-3 in year zero. The cost associated with the construction of beacons in the subsequent years of the life cycle is also shown in the table. The differential GPS architecture incurs a cost in providing the necessary DGPS service. The costs shown in Table 2.5-3 are estimated based on the differential GPS service operated by the U.S. Coast Guard.

Manufacturing costs are primarily the costs associated

with the assembly and test of each navigation system. The assumption is made that 5000 units will be produced in year one, 7000 units will be produced in year two, 10,000 units will be produced in year three, and 12,000 units will be produced in years four and five. The number of units produced is independent of the type of architecture used and is based on anticipated demand for the product. The manufacturing cost for the GPS and DGPS architectures should be about \$2000. The cost of the combined GPS/GLONASS system should be slightly higher, or about \$2100. Since the inertial system is factory installed, its cost is estimated to be \$1500. The costs provided in the tables are determined using these values.

The operations and maintenance costs are also broken down into two categories. The categories are system/product maintenance and inventory. The expected maintenance costs are based on the number of navigation units produced in each year of the life cycle. For the GPS and DGPS architectures, four hours of maintenance per year for each unit at a rate of \$50 per hour is expected. Five hours of maintenance per year at the same rate is anticipated for the GPS/GLONASS architecture since the technology is new. For the inertial navigation system, the number of maintenance hours will probably be higher because the system is factory installed. The number of hours is estimated to be seven per year. The values in the tables are calculated from these estimates. Finally, the cost

of storing and providing spare/repair parts is considered. These costs are also based on the number of navigation units produced in each year of the life cycle. The cost is about \$50 per unit for all architectures except the inertial system. For this system, the cost is approximately \$30 per unit.

This life-cycle cost analysis shows that the GPS architecture is most economically feasible, while the inertial navigation architecture is the least economically feasible. The cost of the combined GPS/GLONASS architecture is comparable to that of the system using GPS. The life-cycle costs of the differential GPS and inertial navigation systems are high due to the required investment in infrastructure. However, due to the potential benefits offered by vehicle navigation systems and the intended future integration with other vehicle systems, the Government might be willing to subsidize part of the system. This would substantially reduce the costs associated with these technical approaches. Therefore, these methods cannot be excluded based on cost alone.

2.6 Conclusion

The approaches described above are all feasible methods for implementing an improved vehicle navigation system. Table 2.6-1 summarizes the feasibility study. The different

Table 2.6-1. Summary of feasible systems.

<u>System Architecture</u>	<u>Accuracy (meters)</u>	<u>Probability</u>	<u>After-market Option</u>	<u>Level of Investment in Infrastructure</u>	<u>Life-cycle Cost (millions)</u>
1. GPS	100	95%	YES	LOW	75.454
2. GPS/GLONASS	40	NDA	YES	LOW	85.378
3. Inertial	5	NDA	NO	HIGH	165.890
4. DGPS	10	95%	YES	MED./HIGH	106.615

NDA = no data available

approaches should be evaluated on the basis of cost, accuracy, and practicality (Rillings, p. 34). Based on these factors, the system using DGPS is the best choice.

A vehicle navigation system using DGPS will provide a great degree of accuracy while maintaining the integrity of the system. The current manufacturers of vehicle navigation systems realize that once people become familiar with electronic navigation, "motorists will want to pinpoint their locations to ten metres or less - the difference between identifying a specific road crossing and an entire city block on a video map" ("Vehicular...", p. 72). In addition, DGPS receivers are expected to become as popular as the GPS receivers are now with mariners. "First, initial prices will be high. Second, DGPS modules will become available to upgrade current GPS units. And third, prices will fall as the market booms" (Skorupa, p. 90).

3.0 Operational Requirements

3.1 Mission Definition

The objective of the vehicle navigation system is to enable users to know where they are at all times. This goal is accomplished by determining the location of the vehicle and tracking that location on a moving-map display. The system should allow the driver to choose the desired destination and see that destination on the map. While driving, the user should be provided with information to aid in making decisions regarding the route to take. This system is primarily intended for use in the continental United States.

3.2 Performance and Physical Parameters

3.2.1 Overall System

Since this system is to be offered as an after-market option for automobiles, the required equipment should be easy to install. The components must be of a size that is suitable for all standard, mass-produced automobile models. The display screen should be large enough to adequately show the location of the vehicle, while providing adjustable levels of detail for the maps. A minimum of nine different map scales

should be provided. The screen should be no smaller than four and one-half inches (diagonal). It can be mounted with a stalk or on the dashboard. The mounting would depend on the particular application of the vehicle navigation system. For instance, if the system was being installed in a police car or an ambulance, the passenger should be able to see and read the display to navigate since it would probably be more beneficial. Therefore, a stalk should be used since it will allow the display to be moved. The combination navigation computer and CD-ROM player should be no larger than 5 X 10 X 13 in, so that it can be mounted in the trunk or other suitable location inside the vehicle. For the compass and sensors, size is not a consideration since the differences will be small and not affect installation.

The moving-map display should be updated once every second with the vehicle's current location. While the vehicle is moving, the top of the map should correspond to "straight ahead." The driver should be provided with enough information to allow for easy guidance. The user should be able to perform several basic functions such as choosing destinations and programming them into memory for recall at a later time. The system should be able to store at least 99 destinations. It should also provide the capability to correct for errors.

The vehicle navigation system should allow for expandability. The use of a menu to perform different

functions will allow additional features to be incorporated at a later time without having to change the hardware. For example, map databases are expected to include information on service facilities, hotels, and restaurants in the future. The menu can be modified to enable the driver to obtain a listing of one of these nearby points of interest. The characteristics of the vehicle navigation system should be aimed at user friendliness.

Due to the large number of receivers on the market today, the main requirements for the differential GPS receiver to be used in the vehicle need to be defined. Accuracy is not a consideration since every receiver should provide the position accuracy that is possible from the GPS system. Two of the main requirements are the time to first fix (TTFF) and the position update rate. The time to first fix is the amount of time that it takes the receiver to obtain a position fix after the unit is first turned on. This value should be a maximum of 75 seconds. The update rate should be one second continuous, since there is a requirement for the navigation system to update the moving-map display every second.

Receiver architectures also differ in the number and type of channels used. The channels on a receiver are used to acquire and track the individual GPS satellites. There are two broad groups of receivers, sequencing and continuous. A sequencing receiver uses a single channel that is moved from

one satellite to another to gather data. The receiver can either acquire the satellite and process all of the data before moving to the next satellite, or it can process multiple satellites in the single channel by rapidly switching between them. This latter method is called multiplexing. On the other hand, a continuous receiver can simultaneously monitor four or more satellites. The continuous receiver is best suited for high-dynamic or high-accuracy applications. For both types of receiver, an additional channel can be used to track all other visible satellites. This capability allows the receiver to rapidly switch between satellites when one that is being used is blocked from view, or the new satellite affords better geometry. Based on these considerations, the differential GPS receiver should have at least five channels.

The receiver does not need to be portable since it will be part of the vehicle navigation system. Since it is part of a system, though, it must be an OEM board. OEM stands for other electronics manufacturers. An OEM receiver board is one that is designed for a variety of integration needs. The board itself is not stand-alone. The board must be imbedded in the other equipment. A stand-alone receiver could not be used in the vehicle navigation system.

The differential GPS receiver should also provide the necessary interfaces. The receiver should have one RS-232 port and one RS-422 port. This will allow the device to

connect to the navigation computer and CD-ROM. The receiver should also support the data format set by Special Committee 104 which is used to transmit the DGPS corrections to users. The format is known as RTCM SC-104. The Radio Technical Commission for Maritime Services (RTCM) established Special Committee 104 to set these standards.

3.2.2 Differential GPS Service

The requirements for a differential GPS service depend upon the particular application. In this case, the application is for vehicle navigation. Since a DGPS service is rather extensive, the attempt is made to describe some of the main considerations. There are five critical performance parameters that are used to evaluate radionavigation systems. They are accuracy, availability, integrity, reliability, and coverage. The Federal Radionavigation Plan (FRP), which is issued by the U.S. Departments of Transportation and Defense biennially, defines these terms in the following manner (Creamer, p. 2):

Accuracy - the degree of conformance between the estimated or measured position of a platform at a given time and its true position

Availability - the percentage of time that the services

of the system are usable

Integrity - the ability of a system to provide timely warnings to users when it should not be used for navigation

Reliability - the probability of performing a specified function without failure under given conditions for a specified period of time

Coverage - the surface area or space volume in which the signals are adequate to permit the user to determine position to a specified level of accuracy

The vehicle navigation system should provide an accuracy of 15 meters (2drms). The statistical notation 2drms refers to the fact that the value of 15 meters is two standard deviations away from the mean of zero. This corresponds to a probability of 95 percent. In other words, the vehicle's location should be calculated to within 15 meters of its actual position 95 percent of the time. The availability of the DGPS service should approach 100%. Therefore, a value of 99.9% is required. The coverage refers to the area over which the DGPS corrections are valid and receivable. It will vary from one broadcast location to another due to differences in factors such as atmospheric noise and propagation characteristics. The overall coverage will vary depending on

the extent to which the system has been implemented. The coverage is ultimately expected to include the entire continental United States.

The requirements for reliability and integrity are difficult to establish without some preliminary testing. These performance parameters are derived based on gathered data. The reliability should approach 100%. Therefore, a value of 98.5% is required. Integrity, however, can be quantified by parameters that once again depend on the type of system (Creamer, p. 2). For a vehicle navigation system, the primary parameters are the protection limit and the time to alarm. The protection limit is the vehicle position error that should not be exceeded without notifying the driver. The time to alarm is the maximum amount of time allowed between the detection of an error outside of the protection limit at the vehicle location and the display of an alarm to the driver. These parameters should be derived using the accuracy requirement.

3.3 Use Requirements

The system should be available for use 24 hours a day, 365 days a year. The actual amount of time that the vehicle navigation system will be in use will vary from driver to driver. It will also vary from day to day for each user. The

system is expected to be used by each driver for an average of 3 hours per day.

3.4 Operational Deployment

The vehicle navigation system should be available throughout the continental United States by the year 2000. GPS is expected to be fully operational by the end of 1993. Due to the testing required for the DGPS service, the system will become available to different parts of the country at different times. The major cities in the U.S. should be the first to receive the service since they need the capability the most. Prototype reference stations should initially be deployed in eight cities around the U.S. The cities are Boston, Washington, Atlanta, Dallas, Los Angeles, Seattle, Denver, and Chicago. These regions should provide contrasting environmental conditions for testing.

The number of reference receivers required for each geographic location will depend on the initial size of the area to be covered, among other factors. For instance, Los Angeles will probably require more reference receivers than Washington, D.C. for the system to function effectively. Once these regions are operational, the service should be established in the less populated areas of the U.S.

3.5 Distribution

The distribution of the vehicle navigation system will be accomplished by retail stores that sell electronic equipment, such as car stereo or cellular phone dealers. Therefore, there is no need to establish a separate retail chain. The navigation systems will primarily be sold in the areas where the DGPS service is operational. These areas will initially be the eight cities around the U.S. Sales do not have to be limited to these areas. As previously stated, the navigation system will be able to function using just the GPS signals (without corrections), but will only be able to provide an accuracy of 100 meters. The level of distribution will probably depend on the demand. The retail stores will also be responsible for the installation of the systems if the users choose not to do it themselves. Installation by the seller is highly recommended. The cost of installation should be \$500 or less.

3.6 Operational Life Cycle

The vehicle navigation system is expected to be available as long as the Global Positioning System is operational. The GPS satellites have a life expectancy of seven years. Since GPS is anticipated to be the future replacement for many

existing navigation methods, satellites will be launched as required to keep the system fully operational at all times. The testing of the new satellites, however, will result in outages. The navigation system is expected to function for the life of the vehicle that it is installed in. This time period is anticipated to be 5 years.

3.7 Effectiveness Factors

In order to be effective, the system must be reliable. The individual components should be expected to function for a specified amount of time without failure. For instance, the wheel sensors should be capable of performing adequately for at least one year. Since the average system use is presumed to be about 3 hours per day, the wheel sensors should have a mean time between failure (MTBF) of 1095 hours. The MTBF for the differential GPS receiver will be much higher. The receiver should have a minimum MTBF of 10,000 hours. The mean time between failures for the other system components will be comparable to that of the wheel sensors.

3.8 Environment

Although this navigation system is aimed at automobiles, it should be able to function in any wheeled vehicle such as

buses, trucks, ambulances, and fire engines. As a result, the system will be exposed to a wide variety of terrains. The components of the system must be able to withstand the repeated shocks and vibrations associated with these different terrains. The navigation system should also be able to operate effectively in the temperature range that is experienced in the continental U.S. Normal temperatures experienced in the U.S. range from 0 degrees Fahrenheit to 105 degrees Fahrenheit. In addition, the user must be able to receive differential corrections during any weather conditions that are encountered in a particular area. There are no special transportation requirements since the operational requirements are more stringent.

4.0 Maintenance Concept

The vehicle navigation system is composed of two main components that should be separated in order to establish a maintenance concept. The two components are the in-vehicle portion of the system and the differential GPS service. These two components are discussed in the following sections.

4.1 In-Vehicle System

The in-vehicle component of the navigation system requires three levels of maintenance for support. In-vehicle simply refers to the parts of the system that are resident on the user's vehicle. The different levels are organizational, intermediate, and depot.

4.1.1 Organizational Maintenance

Organizational maintenance activities are performed by the user of the system. At this level, the user should perform routine maintenance such as inspecting the different pieces of equipment in the vehicle. For instance, the wheel sensors should be monitored to ensure that exposure to heat over time is not causing them to melt. If the sensors are damaged, they should be discarded and replaced. New sensors

can be obtained from a retail store that sells the navigation systems. They can be installed by the user or the seller. The distributor is considered the intermediate level of maintenance. The compass and antennas should also be checked for signs of external damage. The same repair procedures described for the wheel sensors apply to these devices.

The CD-ROM map disks have a similar repair policy. The user has the option of cleaning the disks if desired. Most problems with the disks will result from physical damage. The map disks cannot be repaired and should be discarded and replaced. New disks are supplied at the intermediate level by the retail stores. The maintenance of the CD-ROM map disks also needs to be considered from a software standpoint. The disks should be replaced when new versions are available that contain information on new roads and more completely charted areas. Free automatic upgrades should be provided to users through the retail stores by the company that produces the map software and database tools.

The procedures described above apply to situations in which the user is able to identify the faulty component. Any problems that cannot be isolated to a particular piece of equipment in the vehicle should not be handled at the organizational level of maintenance. These problems will normally be discovered through improper functioning of the vehicle navigation system. They might be caused by the

receiver, the display screen, the navigation computer, or the CD-ROM drive. The user should not attempt to repair these pieces of equipment. As with the other parts of the system, the user does not need to have any spare or replacement parts available to support the system. Since the organizational level of maintenance is done by the user, only a basic skill level is required.

4.1.2 Intermediate Maintenance

Intermediate maintenance is performed at the locations where the vehicle navigation systems are sold. The personnel will be responsible for accomplishing fault isolation and replacing the faulty part with a spare. The personnel will not perform repairs on the individual components of the system. The components will be sent to the depot maintenance locations for repairs. The intermediate maintenance locations must have the test equipment necessary to accomplish fault isolation and must have adequate supplies of components as replacement parts. The user is unable to perform these maintenance tasks due to improper test equipment and skills.

As indicated in the previous section, the intermediate maintenance locations should have spare parts available to provide to the users. Spare parts include wheel sensors, compasses, and CD-ROM map disks. Antennas should be provided

by the retail stores, but they will probably have to be ordered from the depot maintenance locations. The turnaround time for ordering parts should be less than one week.

4.1.3 Depot Maintenance

Depot maintenance tasks are performed by the producers of the equipment. The repairs will be performed on the receiver, the display screen, the navigation computer, or the CD-ROM drive. The locations will depend upon which companies are selected to supply the different components. The personnel at these locations will possess advanced skills since they will be isolating and fixing the problems that the intermediate level is not equipped or trained to handle. Therefore, a larger quantity of support and test equipment is required at these locations. The different locations will also be responsible for supplying the intermediate level with the appropriate parts. If the faulty components are repairable, they can be sent back to the intermediate maintenance locations. In addition, piece parts from components that are not repairable can be used to repair other components. This prevents the entire component from being discarded.

4.2 Differential GPS Service

The GPS satellites are maintained by the Department of Defense. The DoD is responsible for notifying users when system failures occur. If a satellite is deemed unusable, a new satellite will be launched to replace it. The satellites will not be repaired while they are in space. The primary type of routine maintenance that is performed is orbit maintenance. Each GPS satellite passes over a DoD monitoring station twice a day, and precise measurements are made on the orbit parameters. These minor errors are transmitted to the particular satellite by the station.

Maintenance on the reference receivers and broadcast transmitters will be performed by the producers of the equipment. The personnel will be responsible for both routine and overhaul maintenance tasks as necessary. The users of the system will never have to directly interface with this component.

5.0 Conceptual Design

5.1 In-Vehicle Architecture

The components of the new vehicle navigation system will be the same as those used for a basic dead reckoning system except for the addition of a differential GPS receiver and two antennas. The system architecture is shown in Figure 5.1-1. The components include two wheel sensors, an electronic fluxgate compass, a DGPS receiver, two antennas, a display screen with the necessary controls, a combined navigation computer and CD-ROM drive, and the appropriate CD-ROM map disks. The navigation computer and CD-ROM drive consist of the hardware and software that is required to determine the location of the vehicle from the information provided by the different sensors.

The differential GPS receiver will be chosen from designs offered by competing suppliers of GPS equipment. The company responsible for making the vehicle navigation systems will not have to produce its own receivers. Makers of GPS equipment will compete to offer the best design that meets the operational requirements. The final decision will probably be based on a trade-off between cost and performance. The receiver can be installed in the trunk of the car with the navigation computer.

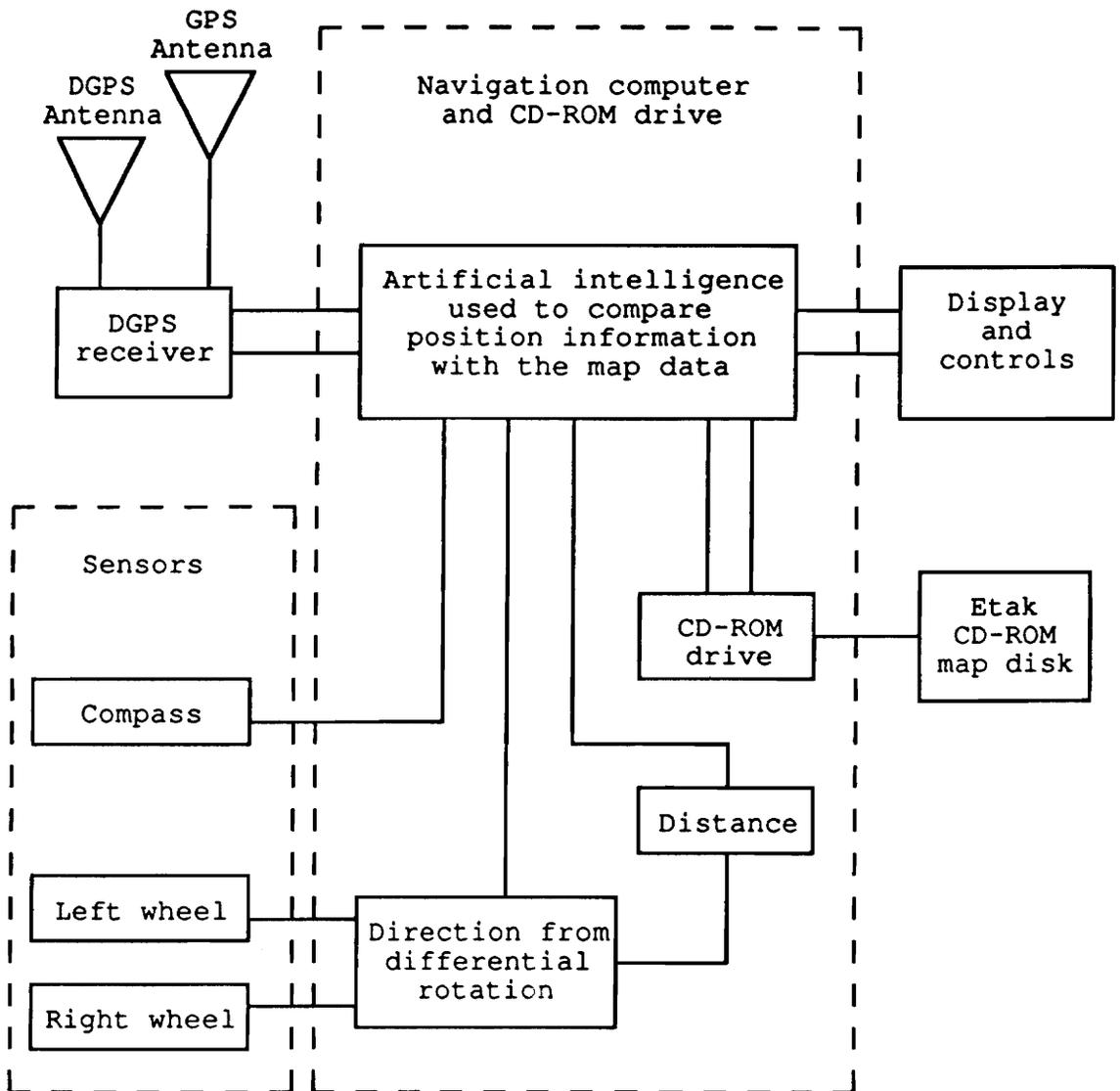


Figure 5.1-1 Vehicle navigation system architecture using DGPS.

The CD-ROM map disks will be supplied by Etak Inc. There are currently five regional maps available and each map disk contains the entire U.S. interstate highway network. Etak has already digitally mapped most areas of the United States. As new roads are built and areas are charted, automatic upgrades for the maps will be given to users.

5.2 Differential GPS Service

The feasibility analysis in section 2.0 showed that the application of differential techniques to the Global Positioning System was the best approach to the design of an improved vehicle navigation system. There are, however, two main methods for implementing the communication link that is required. The communication link allows differential corrections to be broadcast real-time to users. One method is to use a satellite link, and the other method is to use a terrestrial radio link. These design alternatives are analyzed in the following sections. The communication links must be able to meet the operational requirements.

5.2.1 Satellite Link

Figure 5.2.1-1 shows how geostationary L-band satellites can be used to transmit differential corrections to users.

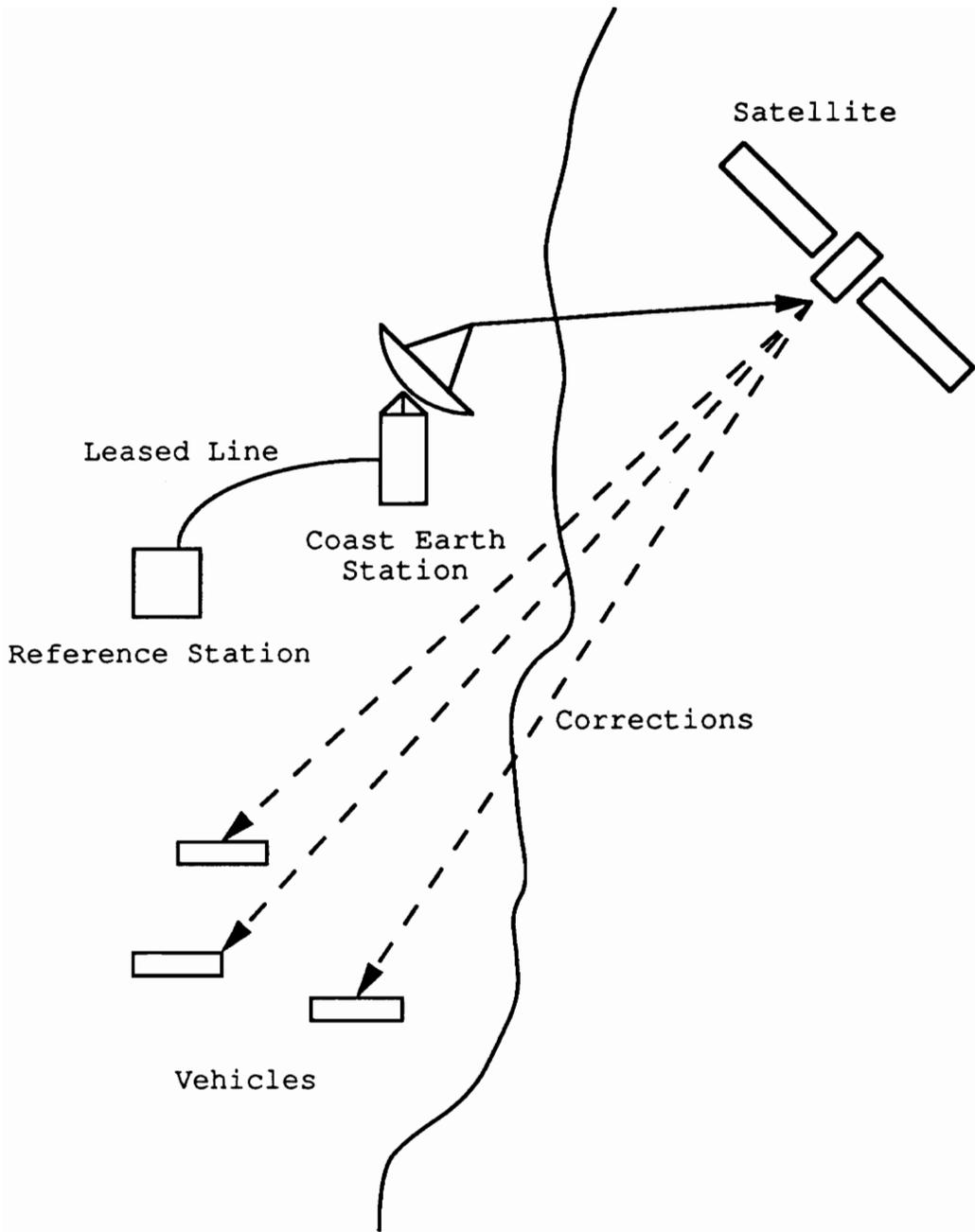


Figure 5.2.1-1. Differential GPS operation using a satellite link.

The reference site receives signals from the GPS satellites and determines what corrections should be applied. These corrections are sent in the standard RTCM SC-104 format to a coast earth station (CES) through a leased telephone line. The data is then uplinked to a satellite so that it can be distributed to users. The reference site is equipped with reference receivers, redundant links to the CES, and an uninterruptable power supply.

This type of link offers several advantages. For instance, a satellite link is able to provide a larger coverage area. This would be useful if global coverage was a requirement. Also, a satellite link offers high reliability. Despite these advantages, Comsat Mobile Communications determined that implementing this communication link for users in small vehicles would not be economical (Williamson). The estimates of the costs involved are proprietary. Currently, Comsat operates this type of system for oil rigs and ships.

5.2.2 Terrestrial Radio Link

Figure 5.2.2-1 shows how a terrestrial radio link can be used to transmit differential corrections to users. The reference station receives signals from the GPS satellites and determines the corrections that users should apply. The broadcast transmitter then sends the corrections in the RTCM

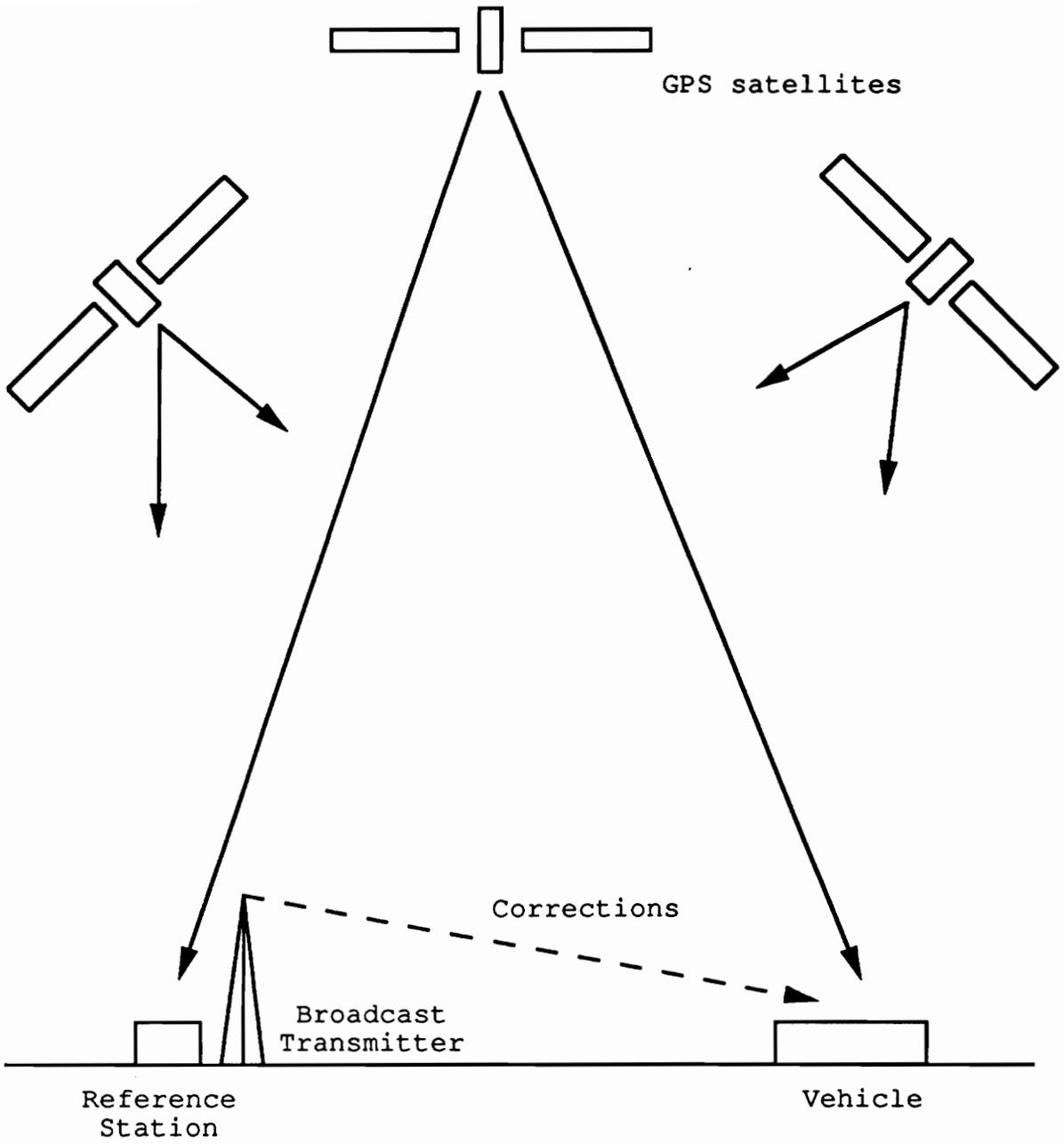


Figure 5.2.2-1. Differential GPS operation using a terrestrial link.

SC-104 format to the users in the coverage area. The reference station and broadcast transmitter do not have to be at the same exact location.

The Coast Guard is in the process of developing a differential GPS service for harbor and harbor approach (HHA) navigation along the coastal United States using this type of link. The Coast Guard chose to use marine radiobeacons to transmit differential corrections "because of existing infrastructure, compatibility with the useful range of DGPS corrections, international radio conventions, international acceptance, commercial availability of equipment and highly successful field tests" (Alsip, p. 4). The radiobeacons use the portion of the Medium Frequency (MF) band from 285-325 KHz to transmit signals. Medium frequencies provide coverage to ranges that are substantially beyond line of sight. The system is expected to be completed by 1996.

A terrestrial radio link is the most feasible method for implementing a differential GPS service for a vehicle navigation system. The remainder of this section will show a design approach for realizing the system. The purpose of the design is to provide a basis for comparison against other possible designs. The main goal of the design is to estimate the number of reference stations that will be required to implement the system, while satisfying the operational requirements. Different designs will vary in the extent to

which they are able to satisfy the operational requirements.

The primary requirement that needs to be satisfied by the design is the accuracy of the vehicle's location as determined by the system. The requirements state that the vehicle navigation system should provide an accuracy of 15 meters (2drms), or 95 percent of the time (reference section 3.2.2). The Coast Guard determined through studies that "accuracy better than eight meters provides no additional advantage to the mariner" (Alsip, p. 6). For a driver, the estimate was made that accuracy better than approximately 15 meters would provide no additional benefit. In order to fulfill this requirement, a value of 10 meters (2drms) will be used in the calculations.

Now, the positional error is approximately equal to the Horizontal Dilution of Precision times the pseudorange error, or

$$\text{pos. error} = (\text{HDOP})(\text{pseudorange error}). \quad (5.2-1)$$

The Dilution of Precision (DOP) is a measure of the accuracy of the position estimate based on the geometry of the satellites being used. The smaller the angle is between the satellites, the worse the position estimate will be. The Positional Dilution of Precision (PDOP) is used when the particular application requires three-dimensional positioning.

Since only two-dimensional positioning is required for vehicles on land, the HDOP is used in equation 5.2-1. Although the worldwide median value of HDOP is about 1.5, it has been determined that 10-meter position accuracy can be achieved when the HDOP is less than 2.3 (Enge, p. 54 and Alsip, p. 6). Therefore, a value of 2.2 is chosen as a worst case value to meet the requirement.

Based on these values, the pseudorange error is calculated to be

$$\text{pseudorange error} = 10 \text{ m} / 2.2 = 4.5 \text{ meters. (5.2-2)}$$

The pseudorange error is the accumulation of the different sources of error which affect the GPS signals. The pseudorange is the approximation of the true range to the GPS satellite. There are many pseudorange error sources, and differential GPS operation is able to reduce some of their effects. The main sources of error and their contribution to the total pseudorange error are shown in Table 5.2.2-1 (Enge, p. 51). These error sources will now be briefly described.

As previously stated, the Department of Defense is able to invoke Selective Availability (SA) to degrade the level of accuracy provided to users. The actual methods used to accomplish this are classified, but SA is known to use a combination of signal dithering and ephemeris manipulation.

Table 5.2.2-1. Pseudorange errors with differential corrections.

Source	Bias Errors (meters)	Random Errors (1drms, meters)
1. Selective Availability	$1.22 \times 10^{-3} t^{2.12}$; $t \leq 40 \text{sec}$	0.0
2. Ephemeris Data	$2 \times 10^{-7} \text{d}$	0.0
3. Ionosphere	$2 \times 10^{-6} \text{d}$	0.0
4. Troposphere	0.5	0.25
5. User Receiver	0.0	0.75
6. Reference Receiver	0.0	0.75
7. Multipath	0.0	0.5
8. Satellite Clock Data	0.0	0.35

In signal dithering, an unknown delay is introduced into the time of signal transmission from the GPS satellite. The effect of this error on the differential correction is based on the age of correction (t). The age of correction is essentially how long it takes the user to receive the differential corrections being transmitted from the reference receiver. Normally, it would be equal to the rate at which the differential corrections are broadcast. However, it changes depending on whether the user is currently able to receive the correction. For example, interference caused by buildings or other large structures can cause the age of correction to vary since the user will not be able to receive the new correction and will have to depend on the old one. There is a limit to the amount of time the user should go without getting an updated correction. The correction is only valid for a certain period of time.

The second item in Table 5.2.2-1 is the error in satellite ephemeris data. This is the bias error that is introduced by SA to reduce accuracy. It is measured in meters. Ephemeris is the parameters that describe the position of the satellite at a particular time in the orbit. The ephemeris data is transmitted to the user in the data message sent by the GPS satellite. The differential GPS pseudorange error caused by this bias is a function of the distance (d) between the user and the reference station.

The next source of error is the delay in the satellite signal caused by the ionosphere. The ionosphere is a layer of the earth's atmosphere from an altitude of 80 to 120 miles that contains electrically charged particles. The density of this layer causes the signal to slow down. The DGPS pseudorange error caused by this delay also depends on the separation between the user and the reference station. If the distance is small, the delays experienced at the location of the user and the reference receiver will be almost equal. As the distance increases, the delays introduced by the ionosphere will vary between each location.

The lower layer of the atmosphere, or troposphere, causes similar problems due to water vapor. These errors, however, are small, and signal delays occur only at very low satellite elevation angles. Very low elevations angles are considered to be below 10 degrees. The error, which has a random component, is usually less than one meter.

The differential correction also suffers from errors due to the user and reference receivers. Differential techniques are unable to reduce either of these errors. The errors in the user receiver are random and caused by factors such as background noise and multiple access interference. An upper bound is estimated to be about 0.75 meters. The errors caused by the reference receiver are the same as those of the user receiver and are transferred to the user in the differential

GPS correction.

Another random error is due to the reception of a signal that has not traveled in a direct path. The signal might have been reflected or bounced by an object or the earth's surface. This type of error is called multipath error. This error is very small and estimated to be below one meter.

The final source of error to be considered is due to the satellite clock. Each GPS satellite has a clock offset, and an estimate of this error is transmitted to the user. There is a random error component, however, that is less than one meter and cannot be removed by differential techniques.

Table 5.2.2-1 shows that the differential GPS pseudorange errors depend on age of correction and the separation between the user and the reference station. The assumption is made that the broadcast transmitter is at the same location as the reference station. The total pseudorange error (1drms) for a user with differential corrections can be calculated by squaring the individual errors, summing them, and taking the square root. The total pseudorange error corresponds to one standard deviation because the random errors in the table are given in this manner. Therefore, in order to use these error estimates to calculate the pseudorange error given in equation 5.2-2, the value in the equation needs to be halved. The new value is given by

$$\text{total pseudorange error} = 4.5 \text{ m} / 2 = 2.27 \text{ m.} \quad (5.2-3)$$

Using this value, the expression for the total pseudorange error can be written as a function of the age of correction and the distance between the user and the reference station. This expression is

$$\begin{aligned} & [1.81 + (1.22 \times 10^{-3} t^{2.12})^2 + (2 \times 10^{-7} d)^2 \\ & + (2 \times 10^{-6} d)^2]^{1/2} = 2.27. \end{aligned} \quad (5.2-4)$$

In this equation, there are two unknowns. There is a limit, however, on the value of t . The age of correction must be below a certain limit to guarantee that the accuracy requirement is met. From equation 5.2-4, it can be seen that the condition that must be met in order for the equation to yield a valid solution is given by

$$1.81 + (1.22 \times 10^{-3} t^{2.12})^2 < (2.27)^2. \quad (5.2-5)$$

Further reduction yields

$$1.49 \times 10^{-6} t^{4.24} < 5.15. \quad (5.2-6)$$

From this equation, the age of correction is found to be 31.5 seconds. This means that the age of correction must be less

than 31.5 seconds to ensure that the accuracy provided by the differential service is 10 meters (2drms).

This limit can be used to derive the parameters described in section 3.2.2 of the operational requirements that relate to the integrity of the system. These parameters are the protection limit and the time to alarm. The protection limit is the vehicle position error that should not be exceeded without notifying the driver. In this case, the protection limit is equal to the desired accuracy of 10 meters. The time to alarm is the maximum amount of time allowed between the detection of an error outside of the protection limit at the vehicle location and the display of an alarm to the driver. The detection of an error corresponds to the age of correction being greater than 31.5 seconds. The protection limit cannot be guaranteed at this point. Based on this maximum value, the age of correction is chosen to be 30 seconds as a worst case value for the calculations. Therefore, the time to alarm is approximately 1.5 seconds. The alarm used to notify the driver could be visual, audio, or both. For example, a light could turn on to alert the driver of the degraded accuracy, while an alarm sounded for three seconds. The light would remain on until an updated correction was received.

The next step is to calculate the distance between the user and the reference station using the age of correction of 30 seconds. Substitution into equation 5.2-4 yields

$$[1.81 + 2.73 + 4.04 \times 10^{-12} d^2]^{1/2} = 2.27, \quad (5.2-7)$$

which results in a value for d of 394.3 kilometers (or 245 miles). This is the maximum distance allowed between the reference station and the user. If the user is farther away, an accuracy of 10 meters cannot be assured. The distance d actually corresponds to the coverage area that should be provided by the broadcast transmitter. It specifies the area in which the differential corrections are valid. The point should be made that this is a simplified design approach. Each transmitter will provide a different amount of coverage due to the differences in atmospheric noise and propagation characteristics for different regions. The actual coverage provided by an individual broadcast transmitter is determined through testing at the particular location. A smaller coverage area guarantees that the accuracy requirement will be met; however, more transmitters and reference stations will be needed to provide complete coverage for a given region.

The next step in the design is to estimate the number of reference stations that will be required to provide coverage throughout the continental United States. Figure 5.2.2-2 illustrates the minimum amount of overlap that can provide complete coverage for a given area. This configuration allows the determination of the minimum number of reference stations and broadcast transmitters that are required to satisfy the

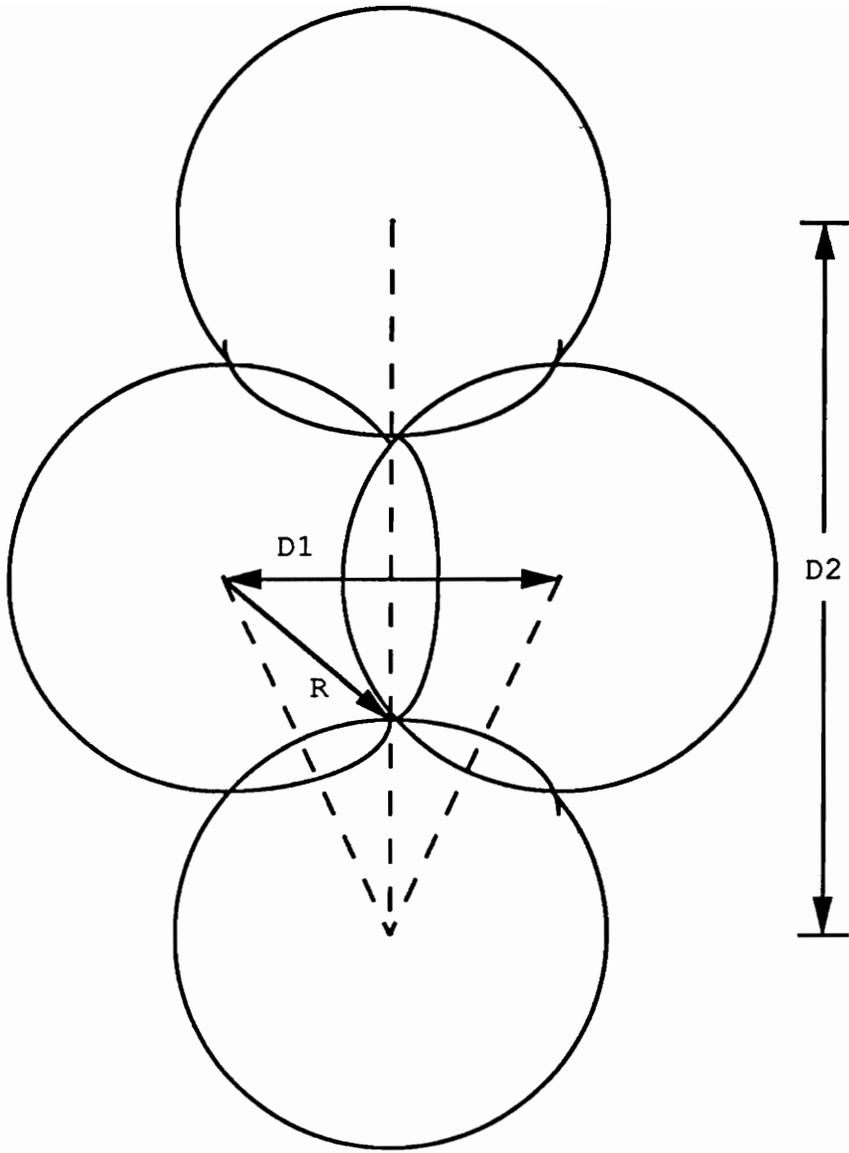


Figure 5.2.2-2. Minimum amount of overlap required for complete coverage.

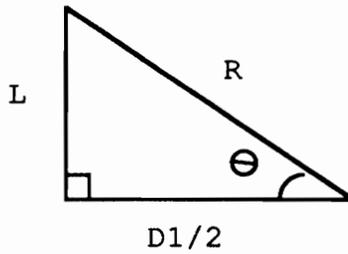


Figure 5.2.2-3. Geometry of coverage variables.

specified accuracy requirement. In other words, the figure shows the maximum latitudinal and longitudinal distances between the broadcast transmitters. The maximum longitudinal distance is given by $D1$, and the maximum latitudinal distance is given by $D2$. The radius of each coverage area is equal to R .

Figure 5.2.2-3 shows the relationship between these variables. Based on the geometry in Figure 5.2.2-2, the value of θ is 30 degrees. Therefore, the value of $D1$ can be derived from

$$\cos(30) = (D1/2) / R, \quad (5.2-8)$$

or

$$D1 = 2R \cos(30). \quad (5.2-9)$$

The figures also show that $D2$ can be expressed by

$$D2 = 2R + 2L. \quad (5.2-10)$$

However, L is given by

$$L = R \sin(30), \quad (5.2-11)$$

and equation 5.2-10 can be rewritten as

$$D2 = 2R + 2R \sin(30). \quad (5.2-12)$$

Now, the value for R has already been determined from equation 5.2-7 to be 394.3 km. Substitution into equation 5.2-9 yields

$$D1 = 2(394.3)\cos(30) = 682.9 \text{ km}. \quad (5.2-13)$$

Similarly, substitution into equation 5.2-12 yields

$$D2 = 2(394.3) + 2(394.3)\sin(30) = 1182.9 \text{ km}. \quad (5.2-14)$$

Using these values, the number of reference stations that are required to provide coverage for the continental United States can be estimated. The average longitudinal distance across the U.S. is approximately 4136.4 km, and the average latitudinal distance across the U.S. is approximately 2090.9 km. The total number of reference stations can be expressed by

$$N = (N1)(N2), \quad (5.2-15)$$

where N1 represents the average number of stations from east

to west (longitudinally), and N2 represents the average number of stations from north to south (latitudinally). These variables can be computed from

$$N1 = (4136.4 / D1) + 1, \quad (5.2-16)$$

and

$$N2 = (2090.9 / D2) + 1, \quad (5.2-17)$$

respectively. Using these equations, the value of N1 is found to be

$$N1 = (4136.4 / 682.9) + 1 = 7.057, \quad (5.2-18)$$

and the value of N2 is found to be

$$N2 = (2090.9 / 1182.9) + 1 = 2.768. \quad (5.2-19)$$

These values are then rounded so that N1 is equal to 8 and N2 is equal to 3. The total number of reference stations is now calculated from equation 5.2-15 to be

$$N = (8)(3) = 24. \quad (5.2-20)$$

This is an estimate of the minimum number of reference stations that would be required to implement the vehicle navigation system with an accuracy of 10 meters. The assumption was made at the beginning of the analysis that the broadcast transmitters would be located near the reference stations.

The results of this design approach can be used as a guideline to determine the potential cost of providing the differential GPS service. The approach attempts to demonstrate the magnitude of the resources involved in the overall system. The evaluation of different designs will focus on a trade-off between cost and performance.

6.0 Functional Analysis

In order to illustrate design requirements, an abbreviated functional analysis of the vehicle navigation system is performed. Figures 6.0-1, 6.0-2, and 6.0-3 show the operational functional flow to three levels. The maintenance functional flow diagrams are derived from these operational functions. Figures 6.0-4 and 6.0-5 show the maintenance functional flow to three levels.

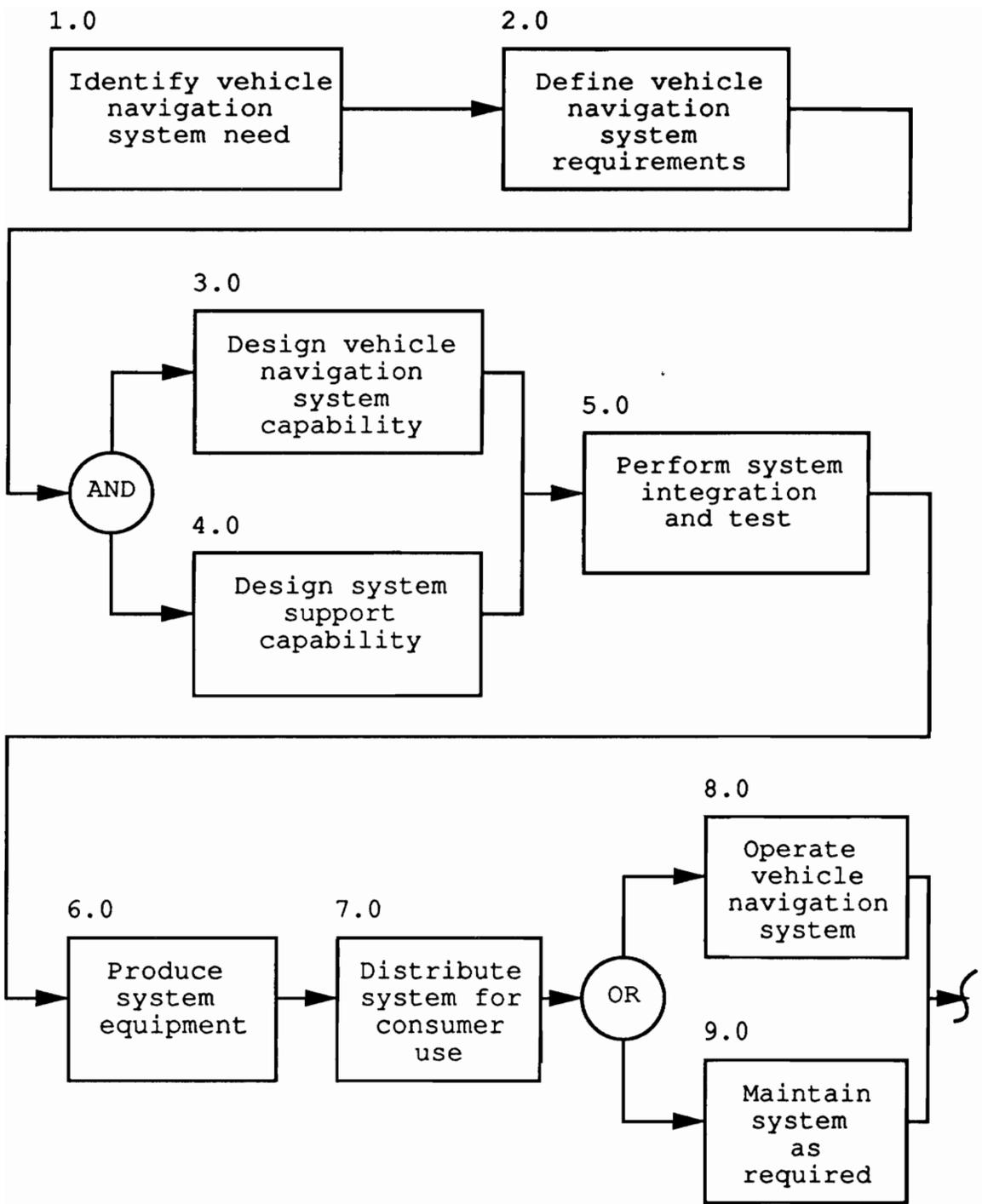


Figure 6.0-1. Operational functional flow - first level.

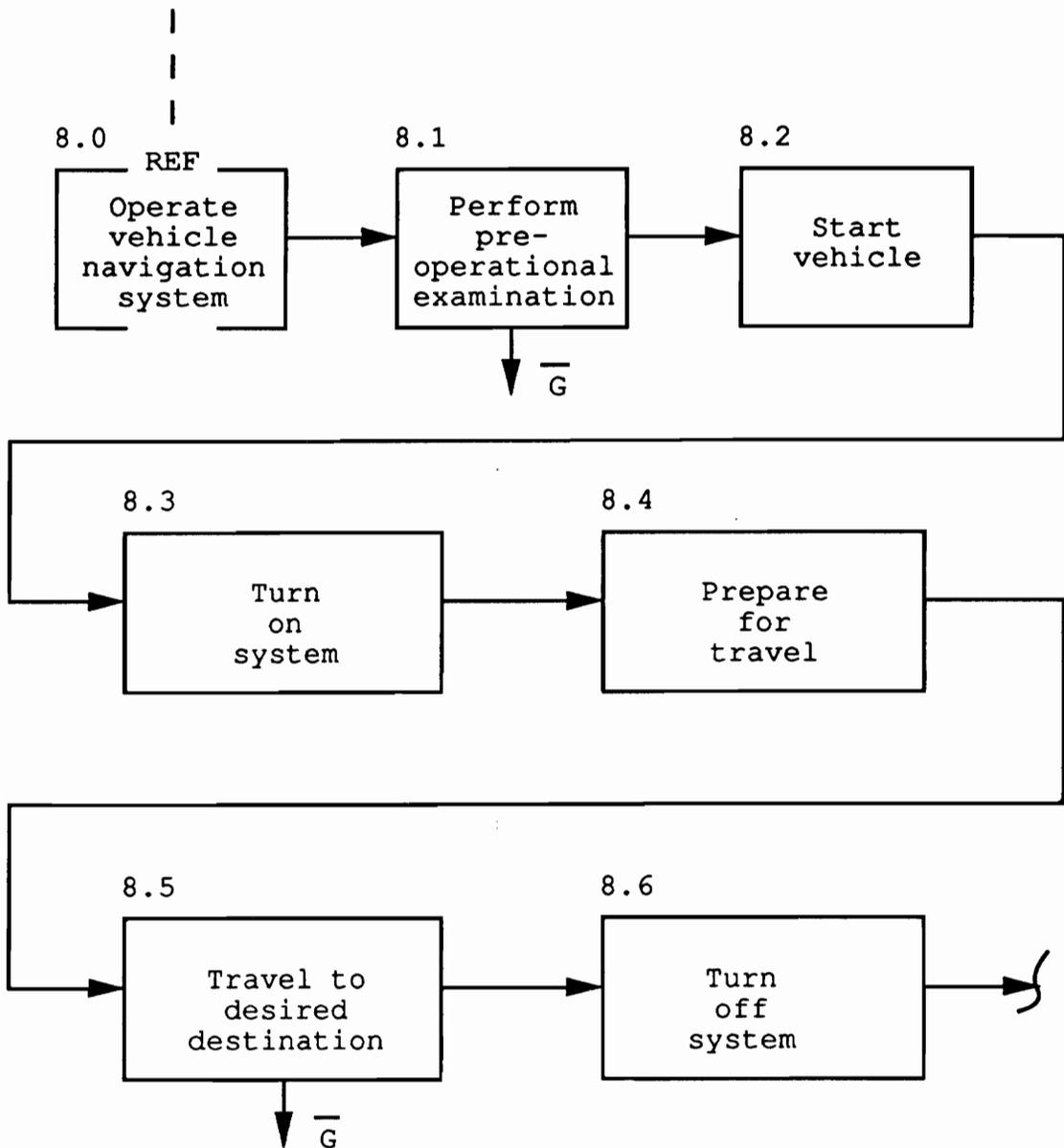


Figure 6.0-2. Operational functional flow - second level.

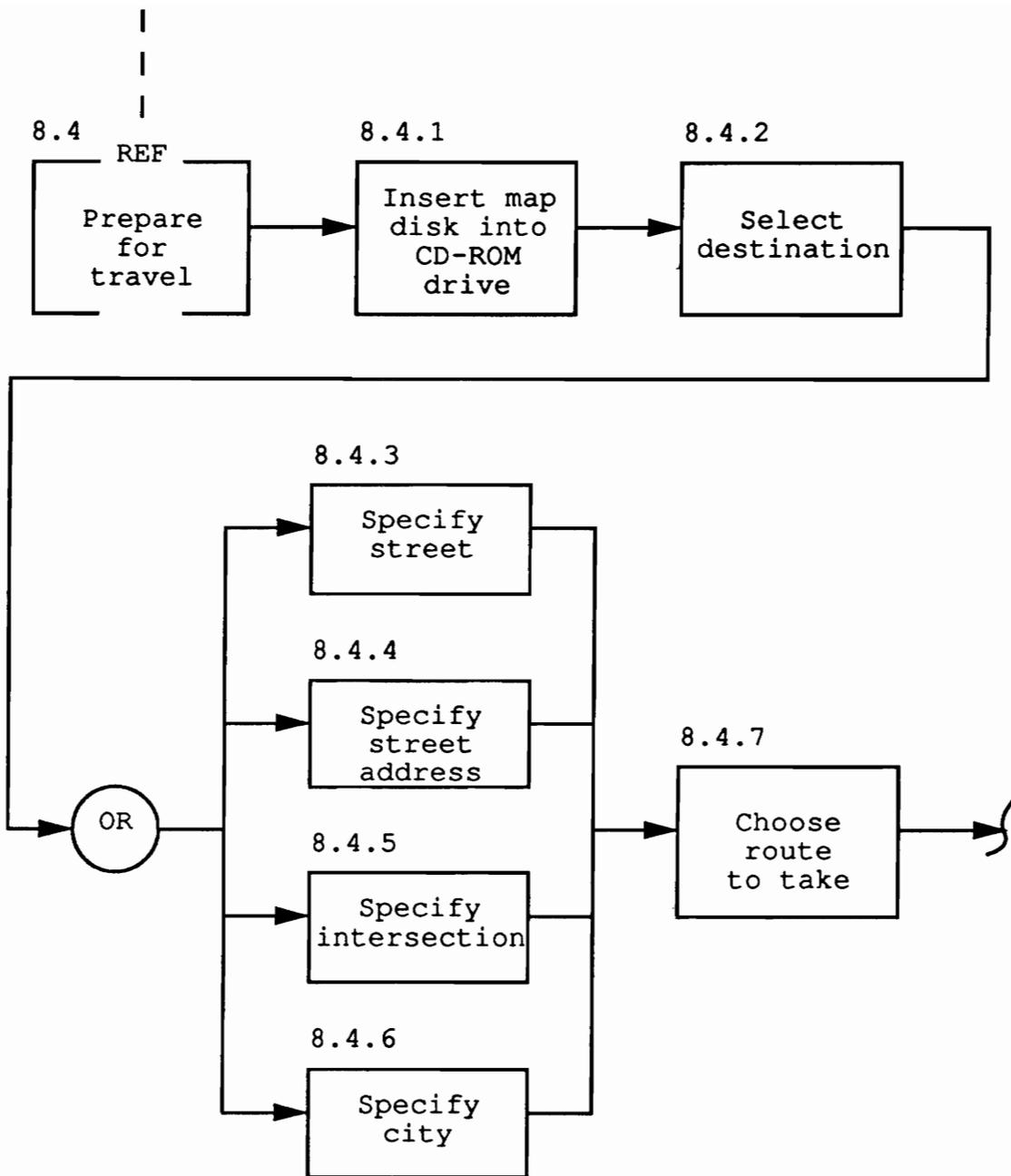


Figure 6.0-3. Operational functional flow - third level.

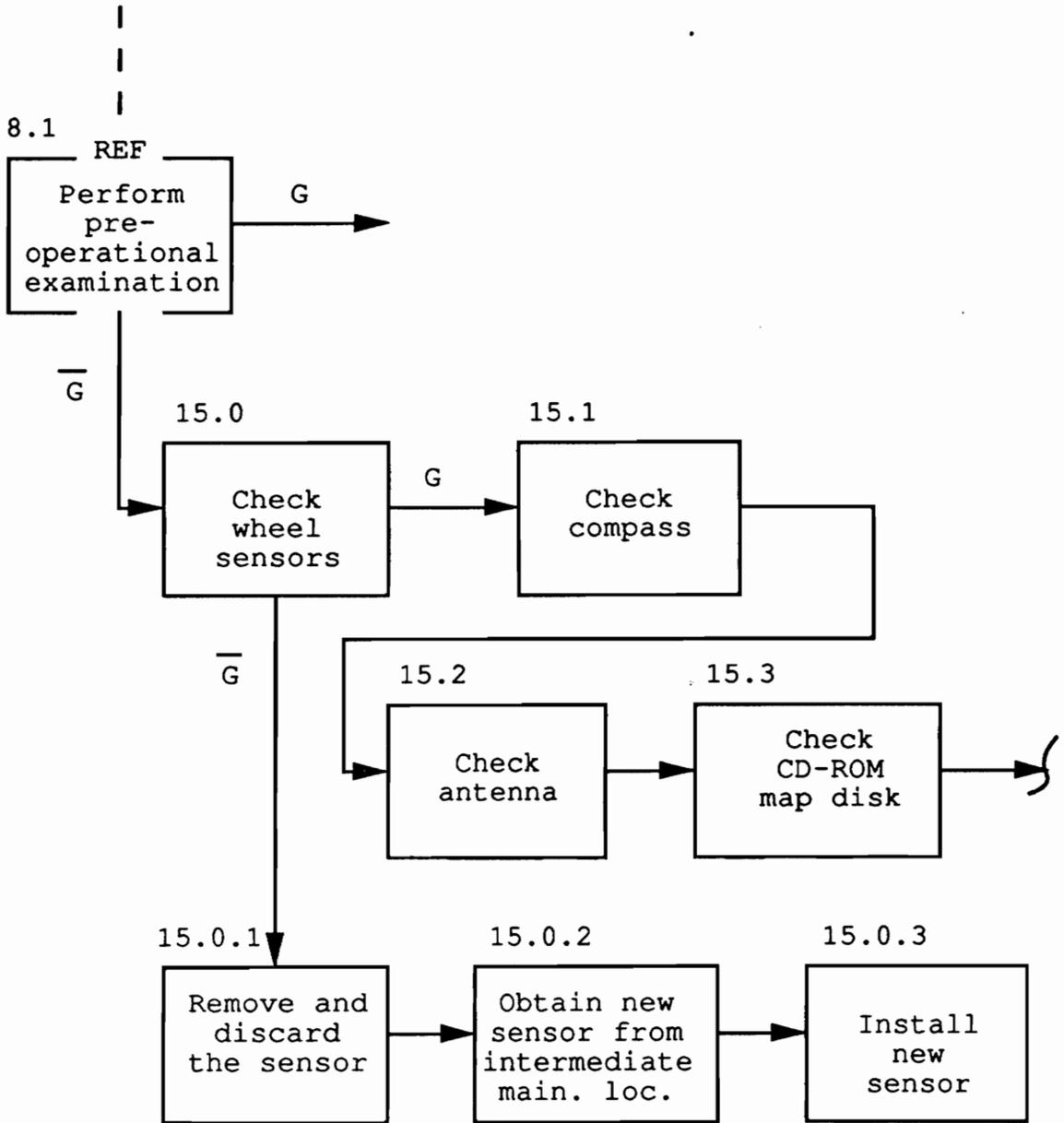


Figure 6.0-4. Maintenance functional flow.

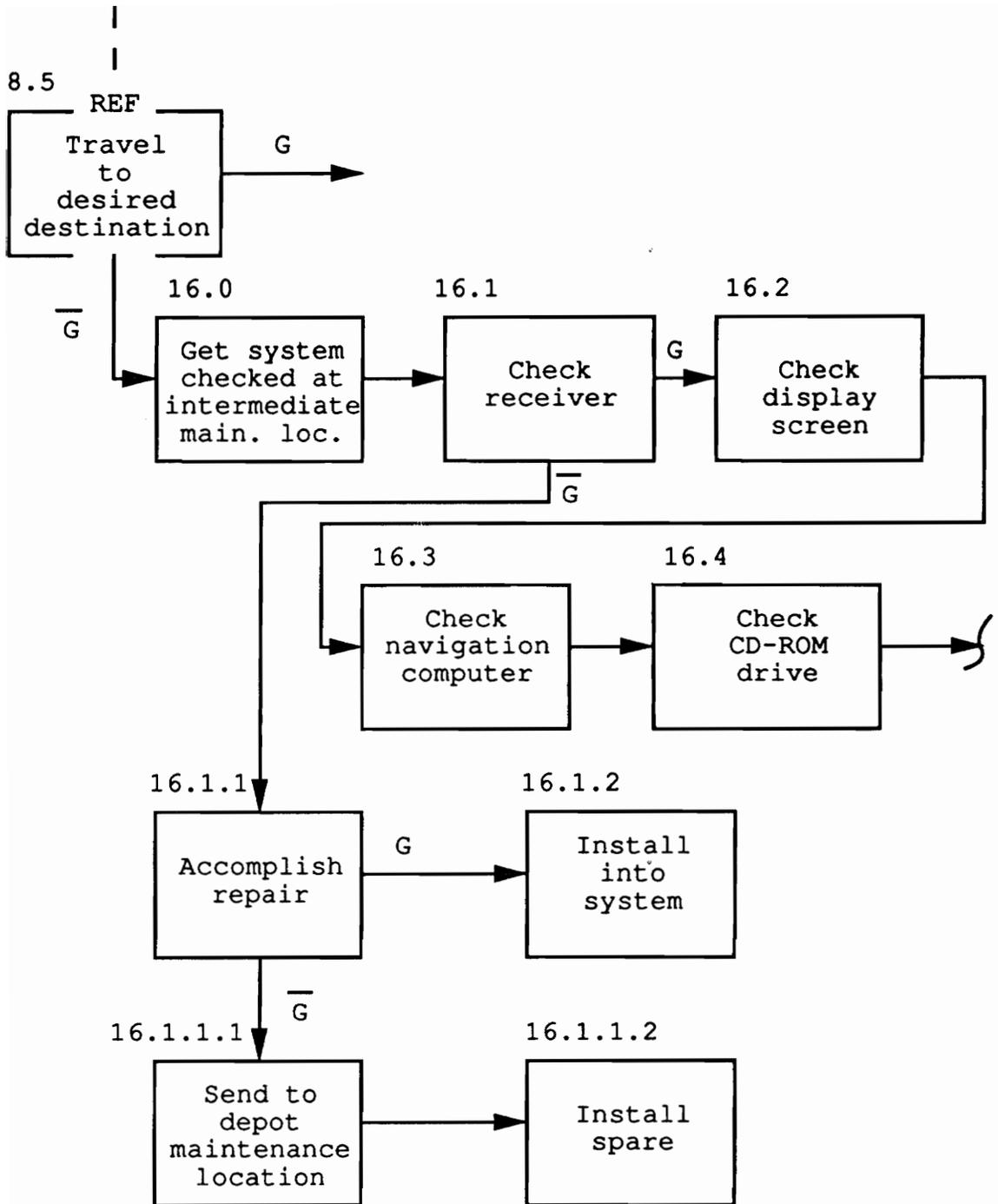


Figure 6.0-5. Maintenance functional flow (cont.).

Conclusion

The purpose of this paper was to provide a systems engineering approach to the design of a vehicle navigation system. Based on the effectiveness of the currently available vehicle navigation system, the development of an improved system is necessary. The most feasible method of implementing the system is to use differential GPS to determine the location of the vehicle.

The use of this method divides the system into two main components. These components are the in-vehicle portion and the differential GPS service. They are addressed separately where appropriate. For instance, the maintenance concept and part of the operational requirements are defined in terms of each individual component.

The conceptual design showed how the system requirements can be met by various technical alternatives. Two types of communication links were described, and the terrestrial radio link was chosen to transmit the differential GPS corrections to users. A design approach was demonstrated to estimate the number of reference receivers that will be required to implement the system.

As previously stated, the design of a vehicle navigation system cannot be completely covered in this paper. However, the systems engineering process was applied to ensure that an

effective system is developed. There are many other factors to consider in the design. For example, the broadcasts of the differential GPS corrections should be monitored in some manner to guarantee their integrity. Also, the different types of data messages to be transmitted need to be defined. These are areas for future research.

Vehicle navigation systems are expected to provide many benefits to users over time. In the future, the CD-ROM map disks will provide information on restaurants, hotels, and other points of interest. Current research and testing on Intelligent Vehicle Highway Systems (IVHS) rely on accurate vehicle navigation systems. These systems are intended to provide users with information on traffic conditions and provide alternate route guidance. An extension of this paper might involve the development of a more comprehensive vehicle navigation system that incorporates this type of information. Also, the method used to provide the user with data on the points of interest contained on the CD-ROM map disks might be described. Whatever the goal, the design of an effective vehicle navigation system is important due to the potential benefits it can provide.

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Appendix: The Global Positioning System

Description

The Global Positioning System (GPS) is a satellite-based system used for positioning and navigation that was developed by the U.S. Department of Defense. The purpose of the system is to provide an unlimited number of users with coverage 24 hours a day under any weather conditions. It is still under development. The fully operational system will consist of 24 satellites. Currently, there are 21 operational satellites, and one was just recently launched. GPS is expected to be fully operational by the end of 1993. When the system does become fully operational, at least four satellites will always be visible to a user from any point on the earth.

GPS provides two different levels of service to users. The Precise Positioning Service (PPS) is available to authorized users and allows positions to be determined to an accuracy of 10 to 20 meters. The Standard Positioning Service (SPS) is available to civilian users of the system and only provides 100-meter accuracy. Each of the GPS satellites transmits signals at two L band carrier frequencies: L1 (1575.42 MHz) and L2 (1227.60 MHz). The PPS uses both of these frequencies, while the SPS transmits on L1 only.

The GPS satellites orbit the earth at very high altitudes

(approximately 20,000 km) and have an orbital periods of 11 hours and 58 minutes. The orbits are able to be predicted with a great deal of accuracy since the satellites are well beyond the earth's atmosphere. Each satellite has four atomic clocks that are used to time the satellite transmissions. The clocks are extremely precise and enable the system to provide its high degree of accuracy.

Determining Position

The basic method used by the Global Positioning System to determine position is known as triangulation. Figure A-1 shows how Lines of Position (LOPs) are used to locate the user. The GPS receiver measures its distance from each satellite, which results in several LOPs. The LOPs are actually Circles of Position (COPs) since knowing the distance from a satellite means that the user is somewhere on a circle on the earth's surface with all points at equal distance from the satellite. The point at which these lines cross defines the location of the user.

If the system was error free, measurements from only two different satellites would be required to determine position in two dimensions. However, the third satellite is needed to correct for any errors in the receiver's clock. The actual LOPs that would be obtained from satellite ranging are shown

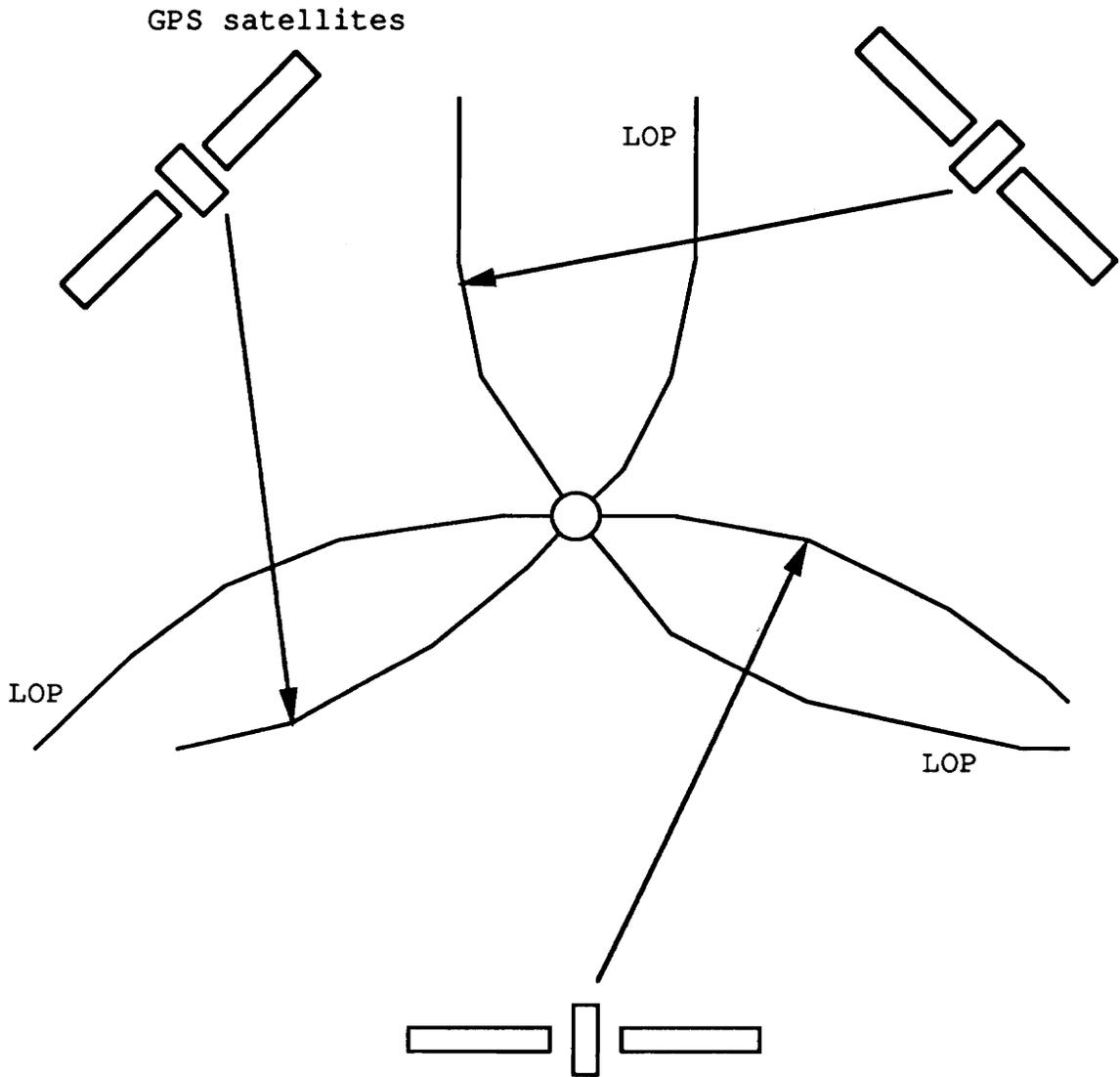


Figure A-1. Determining position using triangulation.

in Figure A-2. The lines would not all cross at the same point. Software in the GPS receivers is able to determine the receiver clock offset that needs to be applied to ensure that the ranges pass through a common point.

The receiver is able to determine the distance from a satellite by measuring the amount of time that it takes for the radio signal transmitted by the satellite to reach the receiver. This is a simple calculation based on the fact that the GPS signals travel at the speed of light. In order to accurately calculate the amount of time, the system was designed so that the GPS satellites and receivers would generate the same code at the same time. The transmission time is found by comparing the time difference between the two codes. Each GPS satellite transmits a different code. These digital codes are referred to as "pseudo-random" codes because they are actually predetermined and repeat every millisecond. The codes are complicated and resemble a string of random pulses.

The difficulty in determining the time it takes the signal to travel from the satellite to the receiver lies in assuring that both clocks are synchronized. Accuracy is not a problem for the atomic clocks aboard the satellites. However, the receiver clocks are not as precise. As previously stated, this is why the third satellite is needed for two-dimensional fixes. The third ranging measurement

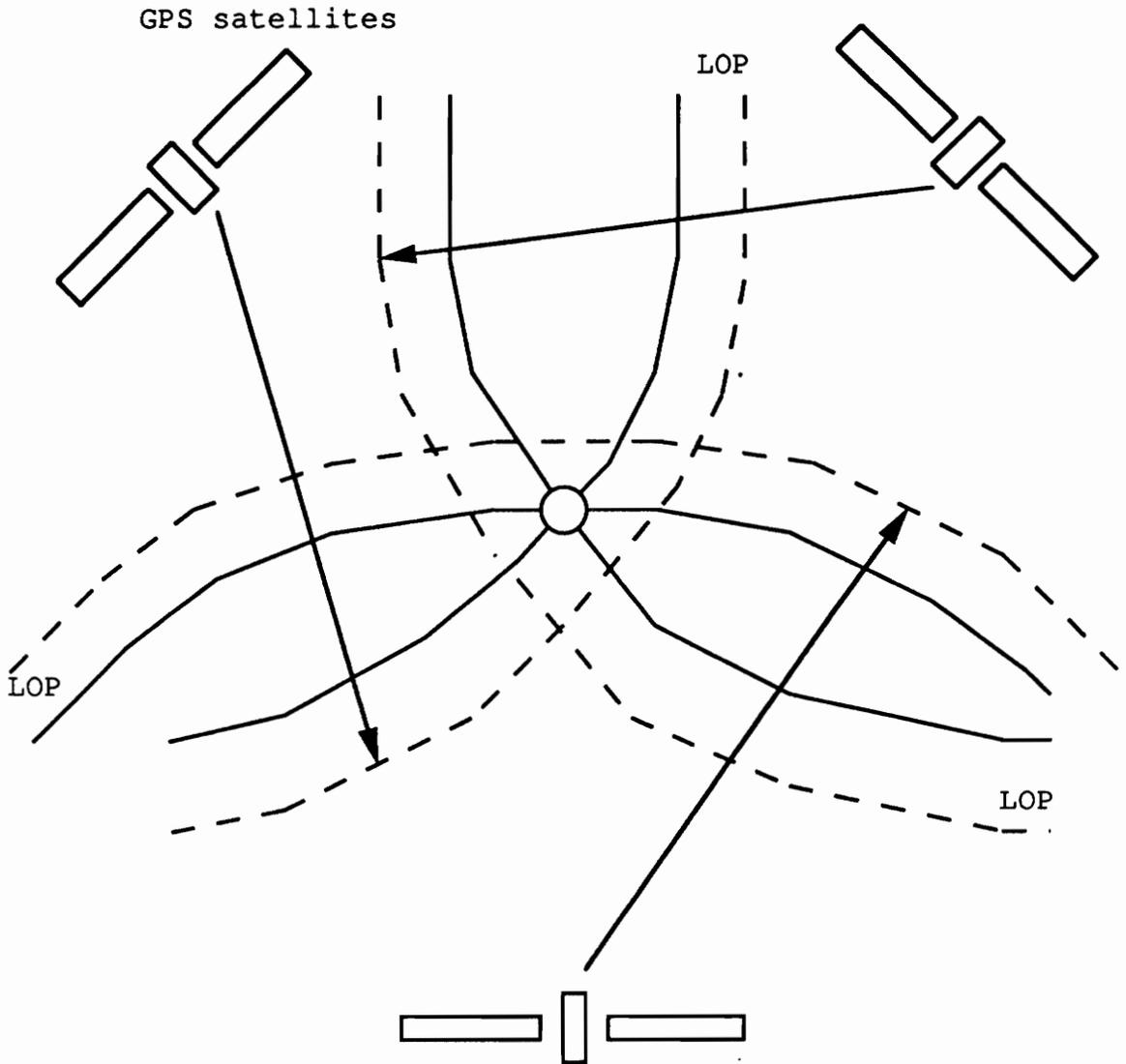


Figure A-2. Using range to determine receiver clock error.

enables the receiver to determine the error in its clock and use that factor to correct the position estimate.

The receiver is also able to determine its distance from each satellite since ephemeris data is transmitted in the GPS signal. The ephemeris data gives the position of the satellite in its orbit over a certain time period. Without this data, the computed distance would have no meaning. Some GPS receivers have an "almanac" which provides the receiver with the location of each satellite throughout its orbit. The almanac also provides information about the health of all GPS satellites. This information is incorporated in the determination of position. Although the method for calculating the position of a user appears to be simple, the technology required to implement the system is very advanced.