Application of Systems Engineering Methods to the Design of an Aviation Navigation System

By

Aaron G. Ankrum

Project Report submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

in

Systems Engineering

APPROVED:

Dr. Timothy J. Pratt, Chairman


October, 1994

Blacksburg, Virginia
Application of Systems Engineering Methods to the
Design of an Aviation Navigation System

By
Aaron G. Ankrum

Committee Chairman: Dr. Timothy J. Pratt
Systems Engineering

(ABSTRACT)

The need for an aviation navigation system is established from examining the phase out of current systems and the delay in the development of replacement systems. The systems engineering approach has been applied to ensure that a capable system is developed. After establishing the need, two GPS based methods of creating an aviation navigation system are examined. A system based on the differential GPS method is chosen as the most feasible.

The functional analysis, operational requirements and maintenance concept are defined based on the differential GPS choice. A conceptual system design is then described for each system element, the ground beacon element and the aircraft element. The allocation of requirements, element architecture and element reliability are examined in the conceptual design.
# Table of Contents

Abstract ........................................................................................................................ ii

List of Figures ................................................................................................................. v

List of Tables .................................................................................................................. v

Introduction .................................................................................................................... 1

1.0 Definition of Need ................................................................................................. 3

1.1 Current State of Navigation Systems .................................................................... 3

1.2 Meeting the Future ............................................................................................... 4

1.3 Benefits ................................................................................................................ 4

2.0 Feasibility Analysis ............................................................................................... 6

2.1 Relative GPS Architecture ................................................................................... 6

2.1.1 Risk Identification and Mitigation ..................................................................... 6

2.1.2 Advantages ...................................................................................................... 7

2.1.3 Disadvantages ................................................................................................. 8

2.2 DGPS Architecture ............................................................................................. 8

2.2.1 Risk Identification and Mitigation .................................................................... 9

2.2.2 Advantages ..................................................................................................... 9

2.2.3 Disadvantages ............................................................................................... 10

2.3 Conclusions .......................................................................................................... 11

3.0 Operational Requirements ................................................................................... 12

3.1 Mission Definition ............................................................................................... 12

3.1.1 Typical Mission Scenario .............................................................................. 12

3.2 Performance and Physical Parameters ................................................................. 13

3.2.1 Beacon receiver system, GPS reception antenna and transmitter antenna .... 13

3.2.2 Aircraft receiver, GPS reception antenna and display .................................. 14

3.2.3 Overall System .............................................................................................. 16
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>Use Requirements</td>
<td>16</td>
</tr>
<tr>
<td>3.4</td>
<td>Operational Deployment</td>
<td>17</td>
</tr>
<tr>
<td>3.5</td>
<td>Operational Life-cycle</td>
<td>17</td>
</tr>
<tr>
<td>3.6</td>
<td>Effectiveness Factors</td>
<td>17</td>
</tr>
<tr>
<td>3.7</td>
<td>Environment</td>
<td>18</td>
</tr>
<tr>
<td>4.0</td>
<td>Maintenance Concept</td>
<td>19</td>
</tr>
<tr>
<td>4.1</td>
<td>Organizational Maintenance</td>
<td>19</td>
</tr>
<tr>
<td>4.2</td>
<td>Intermediate Maintenance</td>
<td>20</td>
</tr>
<tr>
<td>4.3</td>
<td>Depot Maintenance</td>
<td>21</td>
</tr>
<tr>
<td>5.0</td>
<td>Functional Analysis</td>
<td>22</td>
</tr>
<tr>
<td>6.0</td>
<td>Conceptual System Design</td>
<td>27</td>
</tr>
<tr>
<td>6.1</td>
<td>System Architecture</td>
<td>27</td>
</tr>
<tr>
<td>6.1.1</td>
<td>Ground Beacon System</td>
<td>27</td>
</tr>
<tr>
<td>6.1.2</td>
<td>Aircraft System</td>
<td>28</td>
</tr>
<tr>
<td>6.2</td>
<td>Requirements Allocation</td>
<td>29</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Ground Beacon System</td>
<td>30</td>
</tr>
<tr>
<td>6.2.2</td>
<td>Aircraft System</td>
<td>33</td>
</tr>
<tr>
<td>6.3</td>
<td>System Reliability</td>
<td>34</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Ground Beacon System</td>
<td>34</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Aircraft System</td>
<td>35</td>
</tr>
<tr>
<td>7.0</td>
<td>Advanced Application of DGPS</td>
<td>36</td>
</tr>
<tr>
<td>7.1</td>
<td>Additional Data</td>
<td>36</td>
</tr>
<tr>
<td>7.2</td>
<td>Aircraft System Modifications</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Conclusions</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Bibliography</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Appendix 1: Description of the Global Positioning System</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Appendix 2: Description of the Current Instrument Landing System</td>
<td>49</td>
</tr>
</tbody>
</table>

iv
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 3.1</td>
<td>Typical Mission Profile</td>
<td>13</td>
</tr>
<tr>
<td>Figure 5.1</td>
<td>First Level Operational Flow</td>
<td>23</td>
</tr>
<tr>
<td>Figure 5.2</td>
<td>Second Level Operational Flow</td>
<td>24</td>
</tr>
<tr>
<td>Figure 5.3</td>
<td>Third Level Operational Flow</td>
<td>25</td>
</tr>
<tr>
<td>Figure 5.4</td>
<td>First and Second Levels of Maintenance Flow</td>
<td>26</td>
</tr>
<tr>
<td>Figure 6.1</td>
<td>Ground Beacon System Architecture</td>
<td>27</td>
</tr>
<tr>
<td>Figure 6.2</td>
<td>Aircraft System Architecture</td>
<td>28</td>
</tr>
<tr>
<td>Figure 6.3</td>
<td>Overall System Requirements Allocation</td>
<td>29</td>
</tr>
<tr>
<td>Figure 6.4</td>
<td>Ground Beacon System Requirements Allocation</td>
<td>30</td>
</tr>
<tr>
<td>Figure 6.5</td>
<td>Aircraft System Requirements Allocation</td>
<td>33</td>
</tr>
<tr>
<td>Figure 6.6</td>
<td>Ground Beacon System Reliability</td>
<td>34</td>
</tr>
<tr>
<td>Figure 6.7</td>
<td>Aircraft System Reliability</td>
<td>35</td>
</tr>
<tr>
<td>Figure A1-1</td>
<td>Position in Two Dimensions without Error Effects</td>
<td>46</td>
</tr>
<tr>
<td>Figure A1-2</td>
<td>Position in Two Dimensions with Error Effects</td>
<td>47</td>
</tr>
<tr>
<td>Figure A1-3</td>
<td>Geometric Dilution of Precision</td>
<td>48</td>
</tr>
<tr>
<td>Figure A2-1</td>
<td>Localizer Signal Arrangement</td>
<td>50</td>
</tr>
<tr>
<td>Figure A2-2</td>
<td>Glide Slope Signal Arrangement</td>
<td>52</td>
</tr>
<tr>
<td>Figure A2-3</td>
<td>Fan Marker Signal Pattern</td>
<td>53</td>
</tr>
<tr>
<td>Figure A2-4</td>
<td>Localizer Signal Pattern</td>
<td>54</td>
</tr>
<tr>
<td>Figure A2-5</td>
<td>Centered Sideband Signal Resultants</td>
<td>55</td>
</tr>
</tbody>
</table>

List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 3.1</td>
<td>Continental Flight Phase Position Limits and Alarm Times</td>
<td>16</td>
</tr>
</tbody>
</table>
Introduction

The advent of air transportation has seen a technology leap to provide new navigation methods. A great deal of avionics and ground equipment has been developed for the sole purpose of guiding aircraft in their travels and ensuring travel safety. Early on, however, some of the same methods used for ground and oceanic navigation were used for aviation navigation, with varying results. As technology advanced, various systems such as radar, LORAN, and instrument landing systems were created to aid in aircraft navigation. However, as the year 2000 nears, some of these systems are being phased out, needs for the continued safety of nearly 700,000 current general aviation pilots are appearing, and the development of replacement systems has been delayed. Therefore, a need for new aviation navigation system exists.

The goal of this paper is to use the systems engineering process to design an aviation navigation system. The systems engineering process is a step-by-step, iterative method which is primarily concerned with taking a set of requirements and turning them into a product for consumer use. However, this process is an ongoing one, and this paper only illustrates one iteration of how the process works. This single iteration does attempt to demonstrate how the systems engineering process is applied to ensure that a capable system that meets the requirements is developed.

The definition of need is described in section 1.0. The need for a system must be determined before any work is done to actually realize the system. A clear need for the system, such as a required enhancement to an existing system or a gap that a new system can fill, is required. If no clear need is found then there is no need to expend time and money in creating the system. Once a clear need is determined, then the various technical methods for meeting the need can be examined. Section 2.0 describes the two GPS-based methods and the feasibility of each. This section explores the advantages and disadvantages of each method.
Section 3.0 provides the operational requirements of the system. In order to meet those needs, various system parameters are defined. These parameters include performance, physical characteristics, and measures of effectiveness. Also, the projected deployment and distribution methods for the aviation navigation system are described.

A maintenance concept is developed from the operational requirements. This concept is described in section 4.0. The maintenance concept defines the general support environment and the various levels of support required for the system. Early definition of these items during the system development is needed. This early definition allows for incorporation of design features which facilitate ease of maintenance. The objective of this section is to provide specific requirements that can be fully considered at later stages of the design process.

A functional analysis is performed in section 5.0. This analysis is based on the information described in the operational requirements and maintenance concept sections. The analysis section provides an abbreviated visual representation of the various steps required for operational and maintenance actions.

Section 6.0 presents the conceptual design. The goal of this section is to show how the system requirements are met. First, the architecture of each element, ground beacon and aircraft is defined and illustrated. Next, the allocation of system requirements to each system element is derived. Finally, the reliability required for each system element is examined and calculated.

Section 7.0 discusses an advanced application of the DGPS technology in creating an instrument landing system. The required system modifications and extra information required are examined.
1.0 Definition of Need

1.1 Current State of Navigation Systems

The Federal Aviation Administration (FAA) has started a three phase plan to integrate Global Positioning System (GPS) navigation into instrument flight rules (IFR) operations for the United States. Acting FAA Administrator Joseph M. Del Balzo has stated that "... general aviation pilots were the first to advocate use of GPS for aviation, and they will be the first to benefit from an affordable navigation system that can handle all phases of a flight: en route, oceanic, terminal area, and non-precision approaches." (Nordwall 1993). Phil Boyer, President of the Aircraft Owners and Pilots Association (AOPA), indicated that there are almost 200,000 general aviation aircraft and nearly 700,000 private pilots in the United States (Nordwall 1993). These two factors indicate that GPS navigational information will be available across the U.S. and the general aviation market has a substantial base that will want to employ that information.

Additionally, the Microwave Landing System (MLS), which was to become the standard landing technology of the future, has been stalled in its early phases of introduction for civil aviation use. The MLS introduction delay is due mainly to international indecision over technical issues such as data formats and installation time tables. Two airports in Colorado, Aspen and Steamboat, which are currently using MLS, are going to phase those systems out in favor of GPS. As for the current Instrument Landing System (ILS) in use at more than 4000 airports, the FAA will purchase the last system upgrade in 1995, as part a of plan that had expected MLS to be in operation by that time. The FAA also plans to start phasing out primary en route radars in the year 2000, which effect the air traffic control system operations. Both of these actions are a direct result of GPS development plans for civil aviation navigation systems.
1.2 Meeting the Future

Therefore, there exists a need for general aviation pilots to have GPS navigation aids for their aircraft. There also exists a need for regional airports to have GPS landing systems in operation as the older ILS technology will not be supported after 1995 and the MLS technology will not be in use due to a lack of progress in the developmental program. This situation will leave the nation without a viable replacement for the aging ILS technology that will lead to a decrease in safety and support for many of the nation’s airports.

To meet the needs of the general aviation aircraft private owner or fixed-based operator (FBO) who rents out general aviation aircraft, an affordable system is required. Boyer indicates that affordable to the average general aviation aircraft owner means a system that costs between $2,000 and $5,000 fully installed. To meet the needs of a regional airport, the system will have to cost no more than $10,000.

1.3 Benefits

A benefit for the general aviation aircraft owner, other than having a very accurate means of navigation available, is one of cost. Boyer indicates that a $5,000 GPS system could replace as much as $20,000 of traditional navigation equipment (Nordwall 1993). Another benefit, for both pilot and airport, is increased utilization of the airport. A study of the GPS approach into the Aspen airport by Continental Express showed that 26% of their flights would have been cancelled without the GPS technology (Hughes 1993). So, not only will the airports that are losing their current ILSs benefit from GPS based navigation, but many airports that did not have an ILS will benefit. Another cost benefit to the airport operator is that the most expensive element of the system, the GPS satellites, cost them nothing to maintain. The Department of Defense bears that burden. Therefore, the airport operators only need to have the technology that
taps into the GPS system and not a complete support infrastructure of radars, navaids and other associated navigation equipment. A final benefit for all taxpayers may also be realized as the FAA expects to see a large cost savings from the phase-out of many ground-based navaids, such as en route radars, as GPS systems are phased-in.
2.0 Feasibility Analysis

The previous section established that an affordable GPS navigation system is needed for both private pilots and regional airports. There are two technical approaches that can be used to meet the system design needs. The first is relative GPS and the second is differential GPS (DGPS). Both of these approaches are geared to tie the aircraft and airport together in order to aid with navigation around the terminal control area (TCA). A general explanation of the GPS satellite system and how it works is given in Appendix I.

2.1 Relative GPS Architecture

The relative GPS system is based on relative location data from two GPS receivers to provide navigational information. For aviation navigation, the airport has a GPS receiver whose information about the airport location is provided to an approaching aircraft by a fixed beacon with a beacon-to-aircraft datalink. The aircraft then uses this information, in conjunction with its own GPS determined location, to compute a vector to the airport’s beacon. The aircraft uses this vector to derive another vector indicating the touchdown point on the runway. The touchdown point is calculated based on knowledge of the range and bearing to that touchdown point from the beacon.

2.1.1 Risk Identification and Mitigation

In order for this system to work, two technical challenges have to be considered. The first is the pilot’s need for information about the range and bearing from the beacon to the touchdown point. This information could easily be provided by including the information in the standard navigational charts that most pilots use or, by including the information in the data signal to the aircraft. The first method is the easiest to implement and requires less complicated software for the airport and aircraft navigation systems.
The second challenge that must be considered is a coordination method to ensure the beacon and aircraft use the same GPS satellite constellation to determine position. If the beacon and aircraft use a different constellation, there could be a 100-meter or greater instantaneous ranging error. The best method for overcoming this problem is to allow the data link to carry range information from all the satellites it can “see” to the aircraft. The aircraft then matches a sub-set of the beacon satellites to the set it is using.

2.1.2 Advantages

The advantages of this system are cost and time savings over DGPS, the ability to handle a GPS failure, and the accuracy of aircraft position measurements. The cost and time savings are realized by not needing to survey the beacon location precisely. A beacon can be air-dropped to provide instant precision approach capability. This capability can be used for disaster relief efforts, remote airlift and other situations that require the quick deployment of a navigation system.

The handling of GPS errors, such as an on-board signal timing problem with a GPS satellite, is a result of the system design. Since the vectors are based on relative positions, a range error or line-of-sight geometry error induced by GPS satellite failure will apply equally to the beacon and aircraft, when the two are within 25 nautical miles (nm) of each other. Thus both systems will have a common error and the relative fix between the two will not change.

The accuracy of the system is very high. Experiments with the relative GPS system have shown a vertical accuracy of 1.7 meters and lateral (or track) accuracy of 0.72 meters are obtainable (Nordwall 1992). This accuracy level meets FAA Category 1 approach performance requirements which state a maximum vertical deviation of ±4 meters is allowed.
2.1.3 Disadvantages

The disadvantages of this architecture are the current industry concentration, development of aircraft display instrumentation and en route navigation support. Most GPS navigation equipment manufacturers are concentrating mainly on DGPS systems. This situation means that few companies are producing the needed relative GPS equipment which will cause system and parts availability problems.

The second problem of display instrumentation is due to the fact that relative GPS does not supply a direct vector to the touchdown point. Although the beacon-to-touchdown point vector is available from navigation charts, the ability to determine and display the aircraft-to-touchdown point vector is needed. Therefore, instrumentation to relate the beacon location to the touchdown point and to display it must be developed.

Lastly, the maximum range at which the correct vector will not be affected by a GPS failure is about 25 nm. Therefore, at ranges greater than 25 nm, one could not be assured of obtaining the needed accuracy for flight operations.

2.2 DGPS Architecture

The DGPS architecture has the same basic components as the relative GPS system. There is a beacon that transmits its GPS-determined location to aircraft. The aircraft using this signal also is using the GPS to determine its own location. Together, they form a cooperative error correction system. The majority of the error correction is done by the beacon. The location of the beacon is very accurately surveyed and this data is used to correct errors in location generated by the GPS. These corrections are then broadcast for use by the aircraft.
2.2.1 Risk Identification and Mitigation

The main technical challenge is to protect the aircraft and beacon against GPS satellite failures. This problem can be overcome by using receiver autonomous integrity monitoring (RAIM). The aircraft, in determining a 3-D fix for itself, must monitor the signals from four different GPS satellites. If any satellite fails or is producing incorrect data, the 3-D fix will be off by at least 100 meters. The RAIM method for the aircraft requires that the GPS navigation system on board the aircraft be able to monitor at least six different GPS satellite signals. All the signals are then used together to determine if a satellite has failed by cross-checking different combinations of the signals and assuring that they each give essentially the same 3-D fix. If an error is detected, the satellite whose data caused the error is no longer used.

The beacon RAIM error detection is done by monitoring the perceived position of the beacon provided by the GPS receiver there and the known survey position. If the position differential is greater than 15 meters, then the system will change its current set of satellites until it finds a set that provides the correct location data. Note, it is this "truer" set of data that is then used for determining the location error between the GPS-determined location and the survey determined location of the beacon.

2.2.2 Advantages

The advantages of the DGPS architecture are the ability to use existing display instrumentation to present information to the pilot, long range accuracy, and government and industry support. Landing information that is gathered via DGPS can easily be given to the pilot using the existing ILS equipment. This equipment consists of an instrument that has two needles, one horizontal and the other vertical, know as a Course Deviation Indicator (CDI). The horizontal needle indicates how far off, above or below, the plane is from the glide slope for the landing approach. The vertical needle indicates how far
off, right or left, the plane is from the glide slope. Also, current course deviation indicators (CDI) can be used to provide course tracking information derived from the DGPS data. Additionally, all panel-mounted GPS receivers have displays that give information about direction and distance to selected way points.

The availability of DGPS data is only limited to the broadcast range of the beacon used to transmit the signal since there is no need to coordinate the satellites being tracked as with relative GPS. Although current beacon ranges are limited to a 25 nm line-of-sight range, the use of a frequency modulated (FM) signal can extend that range to over 100 nm. This extended range will also allow for the aircraft to track several beacons, thus further enhancing the accuracy of the aircraft’s position. DGPS can provide that position to within 1 meter horizontally and 2 meters vertically.

Finally, both the FAA and most GPS equipment manufacturers are gearing their efforts to DGPS. This situation means that there are government funds available for researching and solving problems with DGPS, and an infrastructure will be created to support it. The infrastructure could be in place as early as 2000. The support of industry means that there will be a wide range of equipment available to the consumer. The situation also means that there will be a large supply of equipment and suppliers to meet the need for spares and servicing.

2.2.3 Disadvantages

The main disadvantage of a DGPS architecture is equipment complexity. Both the aircraft and beacon equipment require extra hardware and software to perform their job, when compared to the relative GPS architecture. The aircraft equipment must be able to track at least six GPS satellites and have software to perform the RAIM checks. The beacon must be able to differentiate the GPS provided position with that of the surveyed position in order to transmit that data to the aircraft. Also, the beacon must have similar RAIM software to that on-board the aircraft.
2.3 Conclusions

Although either architecture is feasible, as the components are the same and available for both designs, the DGPS design offers several advantages over the relative GPS design. DGPS offers the ability to use existing avionics, the ability to provide accurate data over a longer range, and the support of both industry and government. The DGPS system could easily be in place by 2005, when the current ILS systems will be in need of replacement and the infrastructure will be in place by 1998, according to current FAA plans to support the use of DGPS for aviation navigation. Although DGPS is somewhat more complex in terms of hardware and software, the above advantages outweigh any disadvantage encountered due the increased intricacy of the architecture.
3.0 Operational Requirements

3.1 Mission Definition

The objective of the aviation navigation system is to provide the user the ability to handle all possible phases of a continental flight. These phases are en route, terminal area, non-precision approach and landing. The system should use currently available avionics to display the information that is relevant to each flight phase. The system should have the capability to provide information about aircraft position, speed and heading. These goals are accomplished by determining aircraft position in relation to a ground beacon or by simply relying on the sole knowledge of aircraft position to derive the needed information. This system is primarily intended for use in the United States.

3.1.1 Typical Mission Scenario

The pilot enters the aircraft and engages the navigation system. The system provides the pilot with an initial position fix based on data from the GPS satellites and continuously operating airport DGPS beacon system. Once the initial fix is established, the pilot then enters the navigation data for the flight, such as waypoints, final designation, and approach and landing information. The pilot then takes-off and flies the flight plan, using the data displayed on the navigation system display panel and data provided by the navigation system to other aircraft avionics. As the pilot approaches the final designation, the navigation system provides the data necessary to fly the airport traffic pattern and makes a landing, on instruments if necessary. The pilot parks the aircraft and shuts down the on-board navigation system with the rest of avionics. Figure 3.1 illustrates the typical mission profile.
3.2 Performance and Physical Parameters

3.2.1 Beacon receiver system, GPS reception antenna and transmitter antenna

The beacon receiver system must be housed in a weather-resistant electronic equipment shelter. The receiver system must have twelve-channel continuous all-in-view tracking. The receiver system must have a time to first fix (TTFF) of no greater than two minutes and must be able to reacquire within three seconds of signal loss. The receiver system must provide DGPS data once every two seconds. The receiver system must be able to detect faults and provide maintenance personnel, via data capture and a display, information about GPS system errors and internal system faults. The receiver system must provide either integral controls or PC compatible interfaces to allow for system initialization, configuration, updates and downloading of captured data. The receiver system must be able to operate on a standard 120 V alternating current (AC) power source and have the capability to use a DC power source in the event of AC power source interruption.

The GPS antenna must provide hemispherical coverage. The antenna must be
weather-proof and be capable of being remotely located in relation to the receiver system. This requirement provides for flexibility in locating the GPS antenna in a position that is most advantageous for reception of GPS signals. The site of the GPS reception antenna must be the precision survey site.

The transmitter antenna must be sized so as not to obstruct airport operations. The antenna must interface with the receiver system. The antenna must have directional broadcast capability and beam width control. The antenna must be able to handle very high frequency (VHF) signals in the range of 146 - 174 MHz. This VHF range is the typical aviation business band.

3.2.2 Aircraft receiver, GPS reception antenna and display

The receiver, antenna and display portion of the system is intended for both production and after-market installations. Therefore, with the after-market installation in mind, the system should be relatively easy to integrate into the aircraft’s current avionics suite. The receiver must be DGPS compatible and capable of handling RTCM SC-104 GPS correction information. This format was established by Special Committee 104 of the Radio Technical Commission for Maritime Services (RTCM). The receiver must be sized to fit in the standard avionics rack.

The receiver must have six-channel continuous all-in-view tracking. The six channel are needed in order to ensure sufficient GPS satellites have been acquired to perform the continuous tracking. Continuous tracking is a method whereby the receiver uses all available channels to acquire a different GPS satellite on each channel. This technique allows for the ability to switch between satellites as they pass in and out of view. This technique also allows switching to another satellite that provides a better fix due to geometric considerations. The receiver must have a time to first fix (TTFF) of no greater than two minutes and must be able to reacquire within three seconds of signal loss.
The receiver must provide positional updates four times a second. The receiver, in non-DGPS mode, must be able to provide position accuracy, with selective availability disabled, to within 15 meters (2drms) and altitude accuracy to within 35 meters (2drms). The notation (2drms) corresponds to two standard deviations from a mean of 0 meters which translates to a probability of 95%. Therefore, the receiver must achieve this accuracy 95% of the time. The receiver must provide steady-state velocity to within 0.1 knots (kts).

The receiver must be able to accept pre-programmed data cards and user input course track checkpoints, or waypoint plans. The receiver must be able to provide instantaneous range and bearing to and from any point and be able to indicate that information via the display. The receiver must be able to interface with autopilots, altitude-aiding devices, CDI, Horizontal Situation Indicators (HSI), external annunciators and RS-422 ports. The receiver must be able to detect and provide the user, via external annunciators and the display, information about: GPS system errors, navigational fix errors, and internal system faults. The receiver must be able to operate using a direct current (DC) power source.

The antenna must be mountable to the outside surface of the aircraft and must be sized to limit airflow interruption. This size requirement means that the antenna must not exceed 4 inches in width or length, nor exceed 0.75 inches in height. The antenna must be omnidirectional.

The display must present at least two twenty-character lines, produce legible characters and have a brightness adjustment. The display must be able to update information at least four times a second. The display must have reverse video capability for indication of error messages. The display must have integrated controls on the panel that are easy to differentiate and activate.
3.2.3 Overall System

The position accuracy for the overall system must be 1 meters (2drms) horizontally and 2 meters (2drms) vertically. The system must have a line-of-sight (LOS) communication capability of at least 25 nm. The system must detect and provide notification, via aural and visual alarms, of the continental flight phase position deviations as given in Table 3.1.

<table>
<thead>
<tr>
<th>Flight Phase</th>
<th>En route</th>
<th>Terminal Area</th>
<th>Non-Precision Approach</th>
<th>Non-Precision Landing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position Error Limit</td>
<td>+2.0 nm</td>
<td>+1.0 nm</td>
<td>+0.3 nm</td>
<td>+4 meters</td>
</tr>
<tr>
<td>Time to Alarm</td>
<td>30 sec</td>
<td>10 sec</td>
<td>10 sec</td>
<td>1 sec</td>
</tr>
</tbody>
</table>

Table 3.1: Continental Flight Phase Position Limits and Alarm Times

The system should provide for built-in fault detection, isolation, and notification. The notification method will be as noted in Sections 3.2.1 for the beacon system and 3.2.2 for the aircraft system.

3.3 Use Requirements

The beacon portion of the system usage will be continuous (24 hours a day, all year long). The aircraft portion of the system usage will vary upon user. However, an assumed average use will be considered as 10 hours per week.
3.4 Operational Deployment

The beacon portion of the system should be available throughout the United States by 2005. This portion will be phased-in from the present to 2005. The beacon will be offered initially at regional airports that have high-density traffic patterns, difficult approaches and departures, and/or weather-imposed operational limitations. These select airports will provide the needed extremes for system testing and FAA certifications.

The aircraft portion of the system should be available by 1996 for production or after-market installation. In the case of after-market sales, the retailer will be responsible for system installation. The aircraft system cost should not exceed $5000, installed.

3.5 Operational Life-cycle

The beacon portion should have a life expectancy of 30 years. The aircraft portion should have a life expectancy of 10 years. Overall, the navigation system should be maintained for as long as the GPS is operational.

3.6 Effectiveness Factors

The system must be highly reliable in order to provide an effective service. The high level of reliability is required as this system will be the primary means of navigation and its loss could have serious consequences. Therefore, the overall system mean time between failure (MTBF) should be at least 40,000 hours. The mean time between maintenance (MTBM) should not exceed once every six months. The mean corrective maintenance time (Mct) of any system component should not exceed one half-hour. The mean preventive maintenance time (Mpt) on any component should not exceed one half-hour. All components should be maintainable with personnel of technician skill level.
3.7 Environment

The beacon receiver system and transmission antenna must be able to operate in temperatures from -20 to +55 °C. The GPS antenna must be able to operate in temperatures from -35 to +65 °C.

The aircraft GPS receiver and display must be able to operate in temperatures from -20 to +55 °C. The antenna must be able to operate in temperatures from -55 to +70 °C. The antenna must be resistant to de-icing and cleaning chemicals. The complete aircraft system must withstand airspeeds up to 800 kts and accelerations of up to 6 g.

The overall system must be able to send and receive data in all weather conditions.
4.0 Maintenance Concept

The aviation navigation system is comprised of two main elements, the aircraft system and the ground beacon system. However, given the similarity of components and technology, the aircraft and ground beacon elements will be treated as a single system for the maintenance concept.

4.1 Organizational Maintenance

This maintenance function will be performed by the end-user of the system, in accordance with FAA regulations. The aircraft owner will be considered as the end-user of the aircraft system. The airport operations contractor will be considered as the end-user of the ground beacon system. The maintenance tasks the end-user is expected to perform are equipment cleaning, limited equipment adjustments, periodic servicing and limited equipment removal and replacement. These activities will include replacing worn or damaged cables, antennas, and interfaces. The parts to perform these tasks will be available from the intermediate maintenance level, usually the product distributor. Also, the removal of any faulty receivers or transmitters will be performed by the end-user.

Additionally, the end-user will be responsible for monitoring the equipment performance and making any software or interface upgrades. However, the end-user may employ product distributor personnel to make upgrades at cost. Also, any system upgrades should be available at a minimum cost to the end-user.

The above tasks will be described in user manuals supplied by the equipment manufacturer. These manuals will give the criteria for determining if equipment is not functioning properly, procedures that the end-user can perform to trouble-shoot the problem and procedures for forwarding the equipment to the intermediate level of maintenance if the specific fault cannot be isolated. These are items that the end-user
should not attempt to repair, but should rather obtain a new unit to replace the faulty one with and return the faulty unit to the product distributor.

The aircraft system end-user will not need to maintain a supply of spares. This end-user will obtain them from the product distributor as needed. The ground beacon end-user will need to maintain a supply of major system components, such as receivers, antennas and transmitters. This end-user will also need to maintain a supply of any interface components and cables. These supplies are essential as a loss of the ground beacon could have a detrimental effect on the aircraft end-user. These critical parts are to be available within 15 minutes of a request for their need. The ground beacon end-user will obtain the parts from the product distributor. As organizational maintenance is being done mainly by the end-user, only simple skills should be required to perform the tasks.

4.2 Intermediate Maintenance

This maintenance function will be performed at product distributor sites and by mobile teams under product distributor control. The fixed sites will have the equipment needed to perform fault isolation on any system element and the mobile team will be given the specific equipment to perform the maintenance task assigned them. All the intermediate personnel will be tasked with isolating the fault and replacing the malfunctioning item with a spare. They will not be required to repair the malfunctioning item. These items will be sent to the depot maintenance for repairs or disposal if repair is not possible. The intermediate sites will have sufficient supplies of all system components for use as replacement parts. The majority of the maintenance performed by the intermediate personnel will be tasks that the end-user cannot accomplish due to a lack of proper test equipment and/or skills.

As noted in the previous section, the intermediate site will have a sufficient supply of components for end-user installation. These components include receivers,
transmitters, antennas, interfaces, and cables. A supply of these should be maintained by the distributor, but will be ordered for restock from the depot maintenance site. The turnaround time between part order to part delivery at an intermediate maintenance site should not exceed two weeks.

4.3 Depot Maintenance

This maintenance function will be performed by the system equipment producers. Repairs to the receivers, antennas, display panel, and transmitters will be done at these sites. The depot site locations will be dependent upon the source company selected to supply the specific system component. The depot site will have the most complex test and support equipment. The depot site will have highest skilled personnel available for fault isolation. These personnel will be responsible for performing diagnostics and repairs that intermediate level personnel cannot due to a lack of specialized equipment or skills. The depot sites will also be responsible for supplying the intermediate sites with the required spares.

If the depot determines the component is repairable, the appropriate repairs will be made and the item return to stock for issue as a refurbished piece. If the component is deemed not worth fixing, the component will be disposed of properly. The only components that will always fall under this category are the printed circuit boards. In order to provide a low-cost product the consumer, these boards will be consider too costly to repair and are simply replaced. For all other components that are not worth fixing, all parts of the component that can be salvaged will be used for repairs to other components.
5.0  **Functional Analysis**

A condensed functional analysis is done to show the design requirements for the aviation navigation system. Figures 5.1, 5.2 and 5.3 illustrate the operational functional flow to three levels. These figures are derived from the operational requirements. Figure 5.4 illustrates the maintenance functional flow to two levels. This figure is derived from the maintenance concept.
Figure 5.1: First Level Operational Flow
Figure 5.2: Second Level Operational Flow

9.0 Operate System

9.1 Prepare System for Operation

9.2 Obtain Beacon Position Data

9.3 Generate GPS Correction Data

AND

9.4 Provide Data to Aircraft System

9.5 Obtain Aircraft Position Data

9.6 Obtain GPS Correction Data

9.7 Update Position and Display Results
Figure 5.3: Third Level Operational Flow
Figure 5.4: First and Second Levels of Maintenance Flow
6.0 **Conceptual System Design**

6.1 **System Architecture**

6.1.1 **Ground Beacon System**

Figure 6.1 illustrates the ground beacon system architecture. The main system components shown consist of the GPS antenna, GPS receiver, controller, modem, transmitter, and transmission antenna.

![Ground Beacon System Architecture Diagram](image)

**Figure 6.1: Ground Beacon System Architecture**

The GPS antenna captures the signals from the GPS satellites and sends them on to the GPS receiver. The GPS receiver processes the signal and determines the GPS indicated location. This location is then passed on to the controller. The controller is essentially a personal computer. The controller allows for capture of errors, system monitoring, reconfiguration of the system, and other maintenance functions. However, the main task of the controller is to take the GPS determined location and compare it with the surveyed location value to produce the differential correction. The differential correction is then sent to the modem. The modem converts the information into a specific signal for broadcast to the aircraft. This signal is sent on to the transmitter/antenna. The transmitter/antenna broadcasts the signal to the aircraft.
6.1.2 Aircraft System

Figure 6.2 illustrates the aircraft system architecture. The main components shown are the GPS antenna, GPS signal receiver and panel display.

![Diagram of Aircraft System Architecture]

*Figure 6.2: Aircraft System Architecture*

The GPS antenna captures the signals from the GPS satellites and passes them on to the GPS receiver. The GPS receiver then processes these signals to determine the aircraft location in three dimensions. The receiver also provides navigation information, such as course, time to next waypoint, and current location to the display. The display indicates the information from the GPS receiver. The display also allows for the selection of new information to display and programming of the receiver.
6.2 Requirements Allocation

Figure 6.3 shows the overall system allocation of requirements.

![Diagram of Aviation Navigation System]

**Ground Beacon**
- Range: 100 miles
- $A_e$: 0.9998
- MTBM: 4380 hours
- MMH/OH: 0.0001
- Skill Level: Technician
- Cost: $10,000

**Aircraft System**
- Range: unlimited
- $A_e$: 0.92692
- MTBM: 260 hours
- MMH/OH: 0.000025
- Skill Level: Technician
- Cost: $3000

*Figure 6.3: Overall System Requirements Allocation*

The term $A_e$ is the operational availability and MMH/OH is the maintenance man-hour per operational hour. Skill level refers to the capabilities required by the maintenance personnel to accomplish any maintenance task on the unit or system. Cost refers to the amount of capital allocated for producing or acquiring the unit.
6.2.1 Ground Beacon System

Figure 6.4 shows the requirements allocation for the ground beacon system.

![Ground Beacon Diagram]

**Figure 6.4 : Ground Beacon Requirements Allocation**

Equation 6.1 provides the method for calculating the value of $A_o$.

$$A_o = \frac{MTBM}{(MTBM + MDT)}, \quad (6.1)$$

where MDT is the maintenance down time. Equation 6.2 gives the value of MDT.

$$MDT = \overline{M} + LDT + ADT, \quad (6.2)$$

where $\overline{M}$ is mean maintenance time, LDT is the logistics delay time and ADT is the
administrative delay time.

Equation 6.3 gives the value of $\bar{M}$.

$$\bar{M} = \frac{\lambda(M_{ct}) + fpt(M_{pt})}{\lambda + fpt} \quad (6.3)$$

where $\lambda$ is corrective maintenance rate, $fpt$ is the preventive maintenance rate, and $M_{pt}$ is mean preventive maintenance time.

Equation 6.4 is used to calculate the value of $\lambda$.

$$\lambda = \frac{1}{MTBF} \quad (6.4)$$

and Equation 6.5 is used to calculate the value of $fpt$.

$$fpt = \frac{1}{MTBM} \quad (6.5)$$

Substituting the MTBF of 40,000 hours given in Section 3.6 into Equation 6.4 yields a $\lambda$ of 0.000025. Since the beacon system is used year round, there are 8760 hours of operation per year. Therefore, with a MTBM of every six months, that translates to an actual MTBM value of 4380 hours. Substituting this value into Equation 6.5 yields a fpt of 0.000228.

Now, substituting the just determined values of $\lambda$ and $fpt$ and using the $M_{ct}$ and $M_{pt}$ values given in Section 3.6 in Equation 6.3 yields a $\bar{M}$ of 0.5 hours. From section 4.1, the ADT and LDT are given as a total of 0.25 hours. Now substituting all these values into Equation 6.2 yields a MDT of 0.75 hours. Finally, substituting the value of MDT and using an MTBM of 4380 hours in Equation 6.1 yields an $A_0$ of 0.9998.

Equation 6.6 provides the method for calculating MMH/OH.

$$MMH/OH = \frac{(MA \times MI)}{TOPT} \quad (6.6)$$

31
where MA is number of maintenance actions, MI is manhours per maintenance action and TOPT is total number operational hours in the system lifetime. Equation 6.7 gives the value of MA

\[
MA = \frac{TOPT}{MTBF}
\]  

(6.7)

Equation 6.8 gives the value of MI

\[
MI = \overline{Mct} \times PR
\]  

(6.8)

where PR is number maintenance personnel required to correct the problem. Assuming only one technician is required to correct a problem at the organizational level of maintenance and using the given \(\overline{Mct}\) value in Equation 6.8 yields a MI of 0.5 manhours.

Since each unit of the ground beacon system is operated year round, 24 hours/day for 30 years, the TOPT value for beacon system is 262,980 hours. Substituting this value and the given MTBF value of 40,000 hours into Equation 6.7 gives a MA value of 6.5745. Now, substituting the values of MA, MI and TOPT into Equation 6.6 yields a MMH/OH of 0.0000125.
6.2.2 Aircraft System

Figure 6.5 shows the requirements allocation for the aircraft system.

![Aircraft System Diagram]

**Figure 6.5: Aircraft System Requirements Allocation**

The aircraft system is operated 10 hours per week over a year for total of 520 hours of operation per year. Using the general MTBM of six months from Section 3.6, this gives an actual MTBM of 260 hours. Substituting this value into Equation 6.5 yields a fpt of 0.00385. The MTBF for the aircraft system is 40,000 hours. Substituting this value into Equation 6.4 yields a λ of 0.000025. Now, substituting the values of fpt and λ into Equation 6.3 yields a M of 0.5 hours.

The combined value of LDT and ADT found by considering that there is a two week turn around time required to get a replacement part which results in a loss of 20 operational hours for the aircraft system. Therefore, the sum of LDT and ADT is 20
hours. Substituting this value and $\bar{M}$ into Equation 6.2 gives a MDT of 20.5 hours. Finally, substituting the MDT value into Equation 6.1 yields an $A_o$ of 0.92692.

Assuming that only one technician is required to correct an aircraft system problem and using the given $\bar{M}_{ct}$ value in Equation 6.8 gives a $M_I$ of 0.05. The value of $T_{OPT}$ is found by considering that the aircraft system is operated 10 hours per week each year for 10 years which gives a $T_{OPT}$ of 5200 hours. Substituting this value into Equation 6.7 yields a $M_A$ of 0.013. Now, substituting the values of $M_A$, $M_I$ and $T_{OPT}$ into Equation 6.6 yields a $MMH/OH$ of 0.0000125.

6.3 System Reliability

For each system analysis, the antennas are considered to simply be conduits for sending and receiving RF energy. Under this assumption, all antennas will be treated as having 100% reliability since they have no operating components associated with them and all connections to them will be considered as part of the component that interfaces with them.

6.3.1 Ground Beacon System

Figure 6.6 shows the individual component and total long-term system reliabilities. The components are arranged in series.

![Diagram of system components]

System Reliability = 0.999994

Figure 6.6: Ground Beacon System Reliability
Equation 6.9 provides the method for calculating the reliability of a series system.

\[ R = R_a \times R_b \times R_c \times \ldots \times R_x, \]  

(6.9)

where \( R \) is the total reliability and \( R_a \) to \( R_x \) are the individual component reliabilities.

Using the values given in figure 6.6, equation 6.9 yields a system reliability of 0.999994.

### 6.3.2 Aircraft System

Figure 6.7 shows the individual component and total long-term system reliabilities. The components are arranged in series.

![Diagram of Aircraft System](image)

System Reliability = 0.99999

**Figure 6.7: Aircraft System Reliability**

Using the values given in figure 6.7, equation 6.9 yields a system reliability of 0.99999.
7.0 Advanced Application of DGPS

One specific advanced application of DGPS is in an Instrument Landing System (ILS). Current ILSs are terrestrial in nature and sited at each airport that operates one. The current ILS works by transmitting 90 and 150 Hz amplitude modulated signals along the runway. There are two sets of these signals sent out and each of the sets has two of each signal. The signal pairs are each 180° out of phase. The localizer signal provides horizontal course information that allows the pilot to determine how far off the centerline of the runway the aircraft is. The second set provides glide slope information. By using both sets of signals, the pilot can guide the aircraft to a decision point, where the pilot must determine if conditions allow for the continuation of the approach to the touchdown point. This type of approach is called an instrument landing since it is done solely by using the aircraft avionics. Appendix 2 provides more detail on how the current ILS works.

The DGPS navigation system can be used to provide the same information as the current ILS systems being used. The GPS navigation system provides very accurate position information that can be mated with a few easily obtainable data to operate as an ILS. This combination would require no changes to the ground beacon system and only a few modifications to the aircraft system. The following sections explore the additional data needed and what modifications would be required of the aircraft system to create a DGPS ILS.

7.1 Additional Data

There are three sets of additional data that are required: ground, aircraft and derived. The ground data required are the precise location of runway touchdown points, airport elevation in mean sea level (MSL) altitude, any special terrain clearance data, and intersection points. Special terrain clearance data is information that will warn the pilot
that there are ground obstacles that must be avoided on approach, departure, or during a missed approach execution.

Intersection points will act as the fan markers do in the current ILS. They will provide the pilot with the final descent notification, missed approach point, and precision approach point.

The aircraft data required is MSL altitude and the current heading and speed. The MSL altitude is available from the altimeter and the DGPS can provide the current heading and speed.

7.2 Aircraft System Modifications

The aircraft system would need modifications to handle ground data as special waypoints. This indication would allow for glide slope calculation and terrain avoidance. The system would also need the ability to calculate the course deviation from the runway centerline and glide slope on a continuous basis. The aircraft system must be able to convert this data into a format that is usable to the ILS instrumentation. Additionally, the aircraft system must be able to interface physically with the current ILS instrumentation.

The aircraft system must also provide notification of intersection point passage. This notification can be done via the same method as the current ILS does, with a tone in the pilot's headset and blinking light on the CDI for each intersection point. The aircraft system will have to be modified to interface with the aircraft communication system to produce the required tones and the CDI to activate the light.
Conclusions

This paper’s purpose is to demonstrate the application of the systems engineering methodology in designing an aviation navigation system. The need for such a system is analyzed, the options are weighed and one is chosen. Then, using the DGPS option, the systems engineering methods are applied to ensure that a capable system that meets the requirements is developed.

The application of the DGPS method requires two main subsystems. These subsystems are the ground beacon and aircraft components. The subsystems are examined as a single system and independently as needed. As an example, the functional analysis views the subsystems as a single entity but the assignment of operational requirements views them independently.

The conceptual design indicates the basic system components, their arrangement and the levels of reliability and availability needed. The design, while not complex, does require a high level of reliability. The components need to have an average reliability of 0.999997 to meet the requirements. The need for this reliability level is due to safety considerations. A pilot can ill afford to become lost or be unable to make a safe landing. These situations could occur if the pilot does not have a reliable navigation system.

As mentioned in the introduction, the paper’s scope comprises the illustration of a single iteration of the systems engineering methodology and thus is limited. There are system engineering design factors that still need evaluation. For instance, to make sure that the system meets FAA certification requirements, there is a need to develop a test plan. There is a need to develop a methodology for placing and operating en route beacons. These are all factors for further investigation.

The need for a reliable, accurate aviation navigation system is real. The phase out of current systems and the delays in fielding new ones means a gap exists, a gap that a DGPS-based system can fill. Additionally, upgrades to the system are being developed. Added features such as collision avoidance messages, ground traffic control at the airport
and autonomous landing capability are being examined. Additionally, there are possible ways to enhance the system’s functionality such as integrating it with a flight management system or internal navigation system. A possible outgrowth of this paper might entail the development of these capabilities. Overall, the design goal of providing a capable aviation navigation system is significant due to safety needs and to meet aviation’s needs.
Biblography


Appendix 1: Description of the Global Positioning System

System Architecture

The Global Positioning System (GPS) is a space-based positioning and navigation system. GPS was developed and is maintained by the Department of Defense (DoD). The system consists of 24 satellites equally distributed in six orbital planes. The satellites are in orbits of approximately 20,000 km with a period of about 12 hours. The system provides 24 hour coverage, with at least four satellites in view at all times, to an unlimited number of users anywhere on the earth’s surface.

The satellites send their positioning signals on two L-band carrier frequencies. The frequencies are the L1 at 1575.42 MHz and the L2 at 1227.60 MHz. The satellites send and receive operational information on a downlink of 2227.50 MHz and on an uplink of 1783.74 MHz. Each satellite has four highly precise atomic clocks. These clocks provide the required timing accuracy needed to make the system work.

The DoD is responsible for maintaining, monitoring and updating information onboard the satellites that is sent to the users. The DoD is also responsible for replacing and upgrading the satellites. The satellites are known as Navigation Satellite Tracking and Relays (NAVSTARS) and are manufactured by Rockwell International.

Services

There are two levels of GPS positioning services available to users. The first is called Precise Positioning Service (PPS). This service is based on P-code (Precise code) timing and is only available to authorized users. As noted by the name, this service provides the most accurate position fix, usually within 10 meters of one’s actual position.

The other service is called Standard Positioning Service (SPS). This service is based on the C/A-code (Coarse/Acquisition code) timing and is available to anyone with
a GPS receiver. The accuracy of this service is around 30 meters. The PPS transmits both the L1 and L2 links whereas the SPS transmits only the L2 link.

However, since the DoD controls the GPS, the SPS accuracy may be degraded during times of national security threats. This reduction of accuracy is done by using Selective Availability (S/A) mode. This operational mode essentially introduces a deliberate timing error on-board the satellite in order to degrade the obtainable accuracy to around 100 meters.

**Pseudo-random Code and Ranging**

Both the P and C/A codes are digital codes. A casual examination of the signal would seem to indicate that the pulse train of 0's and 1's is random in nature. Nonetheless, the code is specific and known as “pseudo-random” because of this trait. The C/A code is repeated every millisecond. The pseudo-randomness and high repetition rate are needed to perform ranging.

To perform ranging, the satellites all send similar pseudo-random sequences. On the ground, a receiver is generating the same set of codes. When this receiver picks up the signal from a satellite, the code from the satellite and the receiver are compared. The time it took for the signal to go from the satellite to the receiver is found by shifting the received code until it matches the one generated by the receiver. Note, the pseudo-randomness of the code is what makes the match possible by providing an unambiguous correspondence between the two codes being compared. The amount of time shift to make that match is the time of travel from satellite to receiver.

Now, an assumption is made that the signal is traveling at the speed of light in a vacuum, which is not true since some portion of the path is in the atmosphere. This assumption produces some error in ranging, but as will be shown later, there are ways to correct for that. Since time and velocity are known, the distance, or range, to the satellite is found by using the time-distance equation, time \( \times \) velocity = distance.
Calculating Position

Now that the range to each satellite that is in-view can be found, one’s position can be found. For simplicity, the following example is done in two dimensions. To locate a two dimensional (2-D) point, theoretically, only the signals from two satellites are needed. However, to compensate for various errors, three are used. Some of these errors include clocking, ephemeris, and atmospheric errors.

The range from a satellite provides the radius for a sphere in space. This sphere intersects the earth to form a circle. Therefore, the position is narrowed down some location on the circle. The addition of another satellite signal provides another set of intersections that reduces the location down to two points. But, only one of those points lies on the earth and thus the other one can be rejected. The receiver position would now be known, if all was perfect, as shown in Figure A1-1. Since this situation is not the case, the signal from a third satellite is used to help correct the errors. The input from this satellite provides two more points as shown in Figure A1-2. If these points are not the same as the one just found, then the receiver will perform some calculations. These calculations are basically shifting each satellite signal until each set of two provides the same position point. This action allows the receiver to adjust its own clock, which is much cheaper than those on-board the satellites, thus reducing the receiver clocking error. Now, the receiver position is know in 2-D. To find one’s position in 3-D, a fourth satellite signal is required and the same basic calculations are done.

Geometric Dilution of Precision

As noted earlier, there are various sources of error which lead to some uncertainty in determining position. These errors cause the creation of “fuzzy” circles. The place where these fuzzy circles intersect indicates the region where the receiver is located.
However, the geometry between the various satellites’ relative positions can lessen or magnify the effect of the errors as shown in Figure A1-3. Note, the circles around the intersections indicates the region of uncertainty. The effect is known as Geometric Dilution of Precision (GDOP). Figure A1-3 shows that the greater the separation between satellites, the less effect GDOP has. Therefore, a good receiver should take this effect into account by selecting widely spaced satellites to reduce the GDOP.
Figure A1-1: Position in Two Dimensions without Error Effects
Figure A1-2: Position in Two Dimensions with Error Effects
Figure A1-3: Geometric Dilution of Precision
Appendix 2: Description of the Current Instrument Landing System

System Architecture

The current Instrument Landing System (ILS) is a terrestrial-based landing aid. ILS was developed and fielded in 1938 under contract by the fore-runner of the FAA, the Civil Aviation Agency (CAA). The system that operates now still uses the same principles. An ILS consists of three main elements: the localizer, the glide slope, and fan markers. The localizer provides lateral course guidance, the glide slope provides descent angle guidance, and the fan markers provide approach reference points. The following three sections describe in greater detail how each of these elements work.

The Localizer

The localizer consists of an eight antenna array located at the rollout end of the runway which is the opposite end from the touchdown point. The antennas are folded-dipole elements (horizontally polarized antennaeas) that transmit directional signals down the length of the runway. The center two elements send a carrier signal at between 108.1 to 111.9 MHz. This carrier signal is amplitude modulated at 20% with 90 and 150 Hz tones and produce associated sidebands, +90 Hz and +150 Hz. Additionally, a Morse code signal is sent on the carrier using a 1020 Hz tone. This Morse code signal identifies the localizer station and provides a safety measure to ensure the pilot is on the localizer required for landing at the chosen airport. Also, the loss of the identifier alerts the pilot that the station has gone off the air.

The remaining six antennas transmit only 90 and 150 Hz sideband signals, with the carrier being suppressed. The signals being sent from one side of the central antennas are 180° out of phase with those being sent on the other side. Additionally, each set of sideband signals are 90° out of phase with central antennas’ sideband signals. The
The Glide Slope

The glide slope consists of a two antenna array mounted on a 40 foot mast. As with the localizer, the antennas are folded-dipole elements that transmit highly directional signals. The lower antenna transmits a carrier signal at 329.3 - 335.0 MHz. The glide slope carrier signal is always paired with a localizer carrier signal (e.g. if the carrier is 108.1 MHz, then the glide slope signal will always be 329.3 MHz). This arrangement allows the aircraft avionics to automatically select the correct glide slope carrier once the localizer carrier is selected, relieving the pilot of the task.

Both antennas send the 90 and 150 Hz sideband signal. The 150 Hz signal is transmitted in-phase by both antennas and the 90 Hz signal is sent 180° of phase between
the two antennas. However, due to signal reflection off the ground, the reflected 150 Hz
signals are put 180° out of phase and the reflected 90 Hz signals are set in phase. This
signal reflection causes the 90 Hz modulation to be above the glide slope signal and the
150 Hz modulation to be below. Also, as with the localizer, weak components of each
modulation exist on both sides of the glide path. The signal reflection causes the entire
set of signals to appear as being transmitted from the base of the mast, producing the
illusion of a mirror antenna. The combination of the actual and mirror antennas causes
the glide slope to appear as vertical localizer.

The glide slope angle is created by the position of the antennas. The antenna
locations on the mast are set such that the distance between the actual and mirror
antennas are not a 1/2 wavelength multiple of the carrier frequency. This arrangement
produces the desired glide slope angle for carrier, or on-path signal. Usually the on-path
angle is 3°, although terrain conditions at a specific airport may dictate a higher angle in
order to provide a safe approach. The complete signal arrangement is shown in Figure
A2-2.
The Fan Markers

The fan markers consist of simple beacons that produce directional signals. These signals are directed vertically and form an elliptical radiation pattern, as shown in Figure A2-3.
There are three different types of fan markers, outer marker, middle marker and inner marker. Most airport ILSs operate using the first two, which provide a non-precision ILS. The addition of the inner marker allows for precision approaches and is used mainly by commercial airports. The beacons send a 75 MHz carrier signal and the marker type is indicated by Morse code. The outer marker is signified by a continuous series of 400 Hz dashes, the middle marker uses a continuous series of alternating 1300 Hz dots and dashes, and the inner marker a continuous series of 3000 Hz dots.

System Operations

The localizer and glide slope operate in essentially the same manner, so in the interest of brevity, only the localizer operations will be discussed. As noted in the previous sections, various 90 and 150 Hz tones are radiated by the eight antennas of the localizer array. Due to the phasing of the signals, they will cancel each other out in manner the forms pattern shown in Figure A2-4.
Figure A2-4 : Localizer Signal Pattern

The result is that on each side of the carrier signal, a lobe is formed. On one side, the lobe is modulated with only the 90 Hz tone and on the other with only the 150 Hz tone. And because the sideband only antennas cancel each other out completely at the runway centerline, only the original 90 and 150 Hz tones transmitted with the carrier remain. These tones have equal amplitudes since they only have the influence of the carrier to modulate them.

The avionics takes these signals and performs the equivalent of vector math to determine if the aircraft is on the centerline or not. If the tones are thought of as vectors and their amplitudes as their length, the centerline determination is done by computing a simple resultant. If the plane is on the centerline, the two tones have equal amplitude, thus producing a centered resultant, as shown in Figure A2-5.
However, if the plane on either side of the centerline, the sideband lobes will have the effect of weakening one tone’s amplitude while strengthening the other’s, producing a resultant that is not centered. The resultant is presented to the pilot by a vertical needle on the Course Deviation Indicator (CDI). The needle placement is directly proportional to the correction needed to center the plane over the runway. If the needle is left of center, the pilot must correct the plane’s course to the left and vice versa.

The glide slope works in same fashion, with one difference. The glide slope deviation is shown by a horizontal needle on the CDI. However, the correction needed is inversely proportional to the needle location. If the needle is above the on-path indicator, the pilot is below the glide slope and must increase altitude and vice versa.

The fan markers are used as reference and decision points for the pilot. The outer marker is placed three to five miles from the touchdown point. This marker indicates the point where the final descent should start. The middle marker is placed 3500 feet from
the touchdown point and represents the missed approach point, if the airport only has these first two markers. If the pilot cannot see the runway within a few seconds of passing over the middle marker, a missed approach must be declared and the aircraft must abort the landing attempt to try again. The inner marker allows for the pilot to continue to land even if the runway was not visible at the middle marker point, or in other words, allows for a precision approach even if there are clouds within a few feet of the runway surface.