A New Guidance System for Aircraft Based on GPS

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A NEW GUIDANCE SYSTEM FOR AIRCRAFT BASED ON GPS

THESIS

Presented to the MSSS Graduate Committee
of Embry-Riddle Aeronautical University
in Partial Fulfillment of the Requirements

For the Degree of
Master of Science in Safety Science

By

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Prescott, Arizona
May 1, 2004
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A NEW GUIDANCE SYSTEM FOR AIRCRAFT BASED ON GPS

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DEDICATION

Dedicated to the precious two years of my adorable nephew, Sanket’s infancy, that I missed during this period of study, and to my precious, one in a million friend and sunshine, Maria Kritikos, whom I came to know during this short stay in the US. The sweet memories of whose charming persona I will cherish for the remaining years of my life.
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ABSTRACT

The navigation displays commonly used in aircraft (Course Deviation Indicators), provide only the offset from desired track, leaving the pilot to figure out steering correction necessary to get back on track. This correction, determined by trial and error, adds to the workload, especially in windy conditions. The feasibility of using a new algorithm for providing guidance to the pilots for improved interception and tracking is examined in this thesis. The proposed system employs GPS to calculate the offset from the track as well as the instantaneous ground speed vector, to provide steering information. Thus, precise tracking is possible in real time basis, even in high winds.

This research, which served primarily as a proof of concept, involved flying a prototype of the system in different modes of interception and tracking. The flight tests were not intended to obtain statistically significant data but to verify system functionality and promise for further development. The actual courses flown, when compared with the desired course, proved not only the effectiveness of the system but also the ease of tracking, based on displayed guidance commands.
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CHAPTER I

INTRODUCTION

Flight instruments have evolved along with aircraft over the last century. The basic instrumentation necessary for displaying essential flight parameters like airspeed, aircraft attitude, barometric altitude, vertical speed, magnetic direction, turn and slip were developed to provide adequate information for appropriate flight control. The station referenced navigation (i.e. centered on the current VOR/DME also called rho-theta navigation) has been around for over 50 years, having evolved from the four-course ranges of late 1920s, and is in fact, very much in use worldwide, especially over land routes providing for well defined airways. With the advent of navigation systems, like INS, LORAN, and OMEGA in late 1960s, the potential of random/area navigation (RNAV) soon became apparent for economy reasons, both time and money wise. Properly equipped aircraft were no longer constrained to fly the VOR radial defined routes. Now the flights could be routed direct from the origin to the destination, flying great circle routes with the same ease as that of VOR/DME navigation, though the accuracy was not as good.

The advent of satellite based navigation techniques, like the global positioning system (GPS) in late 1980s, revolutionized the field of navigation with accuracy that was by far superior to the existing systems. Even though the system had primarily been designed for military purposes, the possibility of implementing non-precision instrument approaches to hundreds of civil airports in the US without any additional ground infrastructure was soon evident. Within ten years, FAA Technical Standard
Order (TSO) certified, affordable navigation grade receivers became available to be installed even in relatively inexpensive general aviation aircraft. These receivers, powered by powerful microprocessors, not only were capable of providing the essential navigation information, but also could provide information on the integrity and reliability of the system in advance using features like receiver autonomous integrity monitoring (RAIM). Raw navigation data, like the track made good and ground speed, could now be calculated in earth centered earth fixed (ECEF) Cartesian coordinates. Therefore, the errors, due to cross winds, datum conversion, and other effects, on these primary navigation parameters, could almost entirely be eliminated.

The displays for presenting the navigation data, on the other hand, however, seem to have changed little. One such display, the horizontal situation indicator (HSI), presents a pictorial display of navigation situation as a plan view of the aircraft's position and heading with respect to a selected heading and course (Pallet, 1979). One subunit of the HSI, called the course deviation indicator (CDI), includes a movable bar that displays the lateral deviation from the desired radial. The bar is deflected to the left or right for indicating the correction required to stay on course, a VOR radial or ILS beam. The CDI portion of the HSI is also available as a self-contained unit for use with VOR/ILS, but it does not display heading information.

Analogous to navigating with respect to a VOR radial, the navigation with GPS is also with respect to a desired track (DTK) defined by two geographical locations, called waypoints. The cross track error, computed by the GPS, drives the course deviation bar to indicate the direction and magnitude of correction required for
staying on course. “Cross track error is defined as the perpendicular deviation that the aircraft is to the left or right of the desired track resulting from the total error contributions” (RTCA, 1991, Appendix A- p. 2).

Another type of display that originated in the 1960s was that of the flight directors (FD). This display had been conceived with the idea of presenting flight and navigation data in the form of control commands employing servomechanism design principles. This significantly reduced the need for the pilot to assemble basic control data from various instruments, although the pilot had to continuously monitor other instruments as an assurance that all other parameters were consistent with the desired flight objectives (Pallet, 1979). The advantages of such a display included reduced pilot workload as well as greater precision of flight guidance and control.

A FD unit comprises of two principal display subunits: the attitude direction indicator (ADI) and the horizontal situation indicator (HSI). While the HSI subunit is the same as that explained earlier, the ADI presents aircraft attitude and direction information in the form of a three-dimensional display. The attitude is displayed by the relationship of a stationary delta-shaped symbol representing the aircraft, with respect of roll and pitch commands displayed by two pointers, or command bars flanking the aircraft symbol, and also by a horizon bar. The command bars forming a shallow inverted ‘V’ are driven by servomechanisms such that the pilot is always directed to ‘fly into the V’. When a command has been satisfied, the command bars are aligned with the edges of the aircraft symbol (Pallet, 1979). Though popular in larger aircraft, the high price tag associated with it precluded its popularity in general
aviation aircraft. This was because the installation of FD systems involved significant instrumentation, thereby increasing the price.

With the rapid acceptance of GPS for en-route, terminal, as well as approach navigation, aided by the FAA’s publishing of suitable GPS based navigation charts and procedures, it is obvious that this technology is here to stay for a long time. Therefore, attempting to utilize its yet untapped capabilities, like presenting the navigation data obtained from GPS receivers, after minimal processing, in the form of control commands similar to FD systems, is the next logical step. This thesis is a step in this direction and will hopefully further the capabilities of the aviation community without much ado or expense.
CHAPTER II

STATEMENT OF PROBLEM

The deviation indicator bars in prevailing CDI based displays have traditionally indicated the offset from the desired track/radial. If the CDI is coupled with a VOR/LOC receiver, the indicated deviation bar displacement is proportional to the angular displacement of the aircraft from the desired course, which can be approximately converted to lateral distance, if the range from the VOR is known. However, in the case of GPS coupling, this displacement is directly proportional to the cross track error i.e. the scale is linear. For purposes of better precision for staying on course, however, knowing the distance alone from the desired track is not sufficient.

Tracking a route in an aircraft has been modeled as a complex multi-loop control task involving the display-pilot-vehicle system. In this system, the pilot commanding a roll attitude to aileron forms the inner loop, which is based on his perception of heading error - that in turn comprises a secondary loop with respect to a heading reference established by his perception of lateral deviation observed from the localizer displacement (Clement, Jex, and Graham, 1968). If the necessary heading correction information could be conveyed to the pilot in the form of a processed command similar to the FD system, not only will this reduce pilot workload, but also provide superior tracking precision by eliminating pilot computational error.

A study for investigating the influence of CDI sensitivity on pilot tracking error during non-precision approaches was carried out by the FAA Volpe Center in
1991 (Huntley, Rourke, and Disario, 1991). The study concluded that increasing the CDI sensitivity resulted in more accurate flying of the final approach course. This accuracy, however, was offset by the cost of a higher pilot workload and a narrowed visual scan. This demonstrated that increasing the sensitivity of CDI alone, for improved accuracy, was not a viable alternative for a better tracking performance and a better alternative was needed, especially for general aviation aircraft.

With a known desired track, along with actual ground speed and actual track obtained accurately from GPS receiver, the cross track rate (dXTE/dt) will be proportional to the track angle error (TAE). The track angle error is the difference between the desired track and the actual track (track made good). However, since ground speed is not used by pilots for tracking, the heading correction applied for getting back to track is by trial and error, based on his perceived rate of change of XTE obtained from observing the displacement bar movements. This process becomes difficult; especially with changing wind conditions or the routes involving multiple heading changes, as the actual track is a vector sum of the aircraft velocity vector and the wind direction. Hence, the pilot is compelled to try different headings for some time before settling in for a value he deems appropriate for that leg, one that eliminates or at least minimizes the needle “drift” due to crosswinds. Thus, the task of tracking can become demanding when the aircraft is nearing terminal area where aircraft separation is gradually reducing and the task of staying on track assumes growing significance.
The Technical Standard Order, TSO-C129a, the FAA standard for establishing requirements for airborne supplemental navigation equipment using Global Positioning System, requires equipment classified as class A1 (Equipped for En route, terminal and non-precision navigation capabilities) to compute and display TAE to the nearest degree. The display can either be numeric or non-numeric, and the TSO goes on to suggest that "The use of non-numeric XTE data integrated into non-numeric TAE data into one display may provide the optimum of situation and control information for the best overall tracking performance". Studies in 1996 at MIT and the FAA Volpe Center, to investigate the interception as well as tracking performance with the display of supplementary TAE, did substantiate the usefulness of the FAA TSO-C129a requirements on the display of TAE information (Oman, Huntley, and Rasmussen, 1996). The study, using an aircraft simulator for flying approaches, however, was limited to investigating the effectiveness of different means of displaying TAE data along with XTE data and the pilots’ evaluation of each of them based on factors like ease of interpretation, flight path accuracy and overall performance.

This thesis attempts to evaluate the effectiveness of directly providing the desired heading correction to the pilot in order to offset the inadequacies of the existing systems. The magnitude of the desired heading correction, whether intercepting or tracking a route is displayed directly by the extent of the lateral bar deviation. Thus, the pilot’s task of tracking is reduced to merely to making the heading change commanded by the pointer, significantly lowering his workload,
enabling him to devote more time to other crucial activities during approach. This research, while essentially being a proof of concept, due to financial as well as time constraints, however, was limited to the evaluation of the proposed basic concept using prototype hardware. It was not the intent of this study to gather statistically significant data, as it would have involved significant financial investment. Nor was the intent of this study to determine if the CDI pointer used in this prototype setup the best instrument/display to convey the navigation information from the human factors perspective. This will require additional study.
CHAPTER III
DEVELOPMENT OF ALGORITHM

Before delving into the development of the algorithm itself, it would be appropriate to have a brief overview of the terms used in the derivation. Figure 1 below, illustrates the relationship between the various relevant area-navigation (RNAV) parameters.

Figure 1. Different parameters used in area navigation computations and their relationships
Some definitions adapted from the RTCA/DO-208 (1991) and used in relation to magnetic north:

**Desired Track (DTK):** The planned or intended track between two waypoints, measured in degrees from north. [The track itself between the two waypoints is called the course line]

**Track (TRK):** The actual track of the aircraft over the surface of the earth measured in degrees from north. [Also called track made good]

**Cross Track Error (XTE):** Cross track error is defined as the perpendicular deviation that the aircraft is to the left or right of the desired track resulting from the total error contributions.

**Bearing (BRG):** The direction of an object [or Waypoint] relative to a line between the airplane and north.

**Heading (HDG):** The direction toward which the longitudinal axis of the aircraft points as measured clockwise in degrees from north.

**Track Angle Error (TAE):** The difference in degrees (clockwise or counterclockwise) that the track [TRK] is to the desired track [DTK].

**Ground Speed (GS):** The speed of the aircraft measured by the distance the airplane travels over the ground, measured in nautical miles per hour (knots).
Current desired track (CDT)*: The track desired at any time. Examples are:

Constant track made good- Equivalent to constant heading except in terms of ground track.

Intercept track- Instantaneous track required to ensure an intercept angle of desired magnitude (typically 40°) with the DTK.

Currently desired track- Instantaneous track required to correct deviations from the course line. In constant track made good mode, the currently desired track is a constant, equal to the DTK.

CONSTANT TRACK MADE GOOD:

Constant track made good (CTMG) mode of operation is obtained by achieving a track made good of the desired value i.e., providing a track correction that is equal to the difference

\[ \text{Track correction} = \text{Desired TRK - Track Made Good} \]

The difference above has to be corrected to ensure that the Track correction does not exceed ±180°, i.e., it does not provide the larger of the two possible differences.

INTERCEPTION:

Interception can be defined as the task of expeditiously approaching the desired track for smoothly transitioning to it, while minimizing oscillations during the

* Not from RTCA/DO-208
transition phase. For intercepting a track, the pilot aims at achieving a track that provides an intercept angle of about 40° with the desired track.

For positive values of cross track error, i.e. the track lies to the left of aircraft,

\[ \text{Intercept Track} = (\text{DTK} - 40°) \]

However, if this \( \text{Intercept Track} < 0° \) then

\[ \text{Intercept Track} = (\text{DTK} - 40°) + 360° \]

in order to provide for sign correction.

Similarly, for negative values of cross track error, i.e., the track lies to the right of aircraft,

\[ \text{Intercept Track} = (\text{DTK} + 40°) \]

However, if this \( \text{Intercept Track} > 360° \) then,

\[ \text{Intercept Track} = (\text{DTK} + 40°) - 360° \]

in order to provide for sign correction. The \( \text{Track Correction} \), therefore, is given by the difference

\[ \text{Track Correction} = \text{Intercept Track} - \text{Track Made Good} \]

However, if this quantity \(< -180°\) then

\[ \text{Track Correction} = \text{Intercept Track} - \text{Track Made Good} + 360° \]

and, if \( (\text{Intercept Track} - \text{Track Made Good}) > 180° \) then

\[ \text{Track Correction} = \text{Intercept Track} - \text{Track Made Good} - 360° \]

The corrections above are necessary to select the smaller of the two possible angular differences. A positive value of \( \text{Track Correction} \) means a clockwise turn of appropriate magnitude, whereas, a negative value of \( \text{Track Correction} \) implies a counter-clockwise turn of appropriate magnitude.
TRACKING:

As the aircraft closes in to the desired track, the large value of the required track correction has to be gradually reduced. This is necessary, as excessive track correction near track centerline will result in centerline overshoots necessitating heading correction of opposite direction. This will cause not only oscillations about the DTK centerline, but require excessive pilot inputs.

The algorithm developed for tracking is based on the relationship existing between the desired values of rate of change of XTE and the track angle error.
From Figure 2 below, during the tracking phase, the desired rate of change of cross track error can be expressed as

\[
\frac{d(XTE)}{dt} = V_G \sin(DTK - CDT) \\
\approx V_G (DTK - CDT)
\]

Equation (1)

for reasonably small values of (DTK-CDT), both expressed in radians, where \(V_G\) is the ground speed of the aircraft along the track made good. When the TRK is nearly parallel to the DTK, the component of \(V_G\) along the CDT can be approximated to \(V_G\).

*Figure 2. Relationship between the desired rate of change of XTE and ground speed component along cross track direction (all referenced to the ground & shown on an exaggerated scale)*
Also, making the desired rate of change of cross track error proportional to the magnitude of cross track error, we have the

\[
\frac{d(XTE)}{dt} \propto XTE
\]

Equation (2)

\[
= K \ast XTE
\]

where K is a constant of proportionality. Therefore, from Equations (1) and (2) we have for tracking:

\[
K \ast XTE = V_G \ast (DTK - CDT)
\]

and on rearranging the above, the currently desired track is

\[
CDT = DTK - \frac{K \ast XTE}{V_G}
\]

Equation (3a)

However, if this quantity CDT < 0°, then for providing sign correction we have

\[
CDT = DTK - \frac{K \ast XTE}{V_G} + 360°
\]

Equation (3b)

The track correction required is therefore,

\[
Track\ Correction = CDT - TMG
\]

However, if (CDT - TMG) < -180° then

\[
Track\ Correction = CDT - TMG + 360°
\]

and, if (CDT - TMG) > 180° then

\[
Track\ Correction = CDT - TMG - 360°
\]
CHAPTER IV
PROTOTYPE SETUP

HARDWARE

The basic system requirements for the prototype to be used in testing can be summed up as:

- a source of precise navigation data;
- a portable computer for the acquisition as well as processing of navigation data;
- a means for converting digital processed data to analog signals for driving the analog display; and
- a means for displaying the correction data to the pilot (analog display)

SOURCE OF NAVIGATION DATA:

The Novatel OEM-4 receiver was chosen as:

- A unit could be easily borrowed from the ERAU, Daytona Beach Campus.
- It was capable of receiving and tracking the L1 C/A Code, L1 and L2 carrier phase, and L2 P Code (or encrypted Y Code) of up to 12 GPS satellites, providing better Position-Velocity-Time information.
- It was capable of good acquisition and re-acquisition times, a capability that was necessary for flight tests where a separate GPS antenna was required to
be placed inside the aircraft. Therefore, the possibility of certain aircraft maneuvers resulting in momentary loss of satellite signals was high.

- It provided for serial port output of navigation data in NMEA format.
- It was capable of outputting raw navigation parameters like cross track error, speed over ground, track made good (to be used for correction computation) at up to 20 Hz, where as other available receivers could only provide a data rate of 1 Hz. A higher data rate improved the tracking accuracy of track centerline, eliminating jerky movement of display needle.
- It could be operated from a separate carry on rechargeable battery for up to 6 hours, thus avoiding the need to interface with the aircraft power supply that would otherwise have necessitated the work of a qualified aircraft technician.

PORTABLE COMPUTER

A Dell 8600 Notebook was chosen as:

- It had a 15.4' UXGA display to allow the display of all the components of the processing software front panel in different ambient light conditions in flight.
- It was powered by 1.6 GHz CPU to effectively run the LabVIEW based data-acquisition and processing software.
- It had a DB-9 serial port connector for interfacing with the serial port of the GPS receiver for data acquisition. It also had a Type II PCMCIA slot for interfacing with the DA card.
It had a sufficient capacity battery to provide for the continuous operation of up to two hours with maximum screen intensity while driving the needle pointer from its charge reserves.

MEANS FOR GENERATING ANALOG SIGNAL
A DAQCARD™ AO-2DC, analog output card was selected as:
- It is a PCMCIA card for use in notebooks and is manufactured by National Instruments, which also provides LabVIEW driver support for use in the application software.
- Its 12-bit resolution is enough for generating DC signals for driving analog needle at about 4 Hz frequency.
- It was within the project’s budgetary constraints (< $400 for the card and its accessories like the connector block and ribbon cable).

ANALOG NEEDLE DISPLAY
A CDI unit was acquired as:
- An un-airworthy unit with working CDI needle was available at ERAU avionics workshop.
- It is a stable pointer drive compensated/balanced for aircraft movements.
- Pilots are more comfortable with a needle display
CABLES

- The null modem data cable for connecting GPS RX to notebook is the same provided with the GPS receiver.
- The cable connecting the DA card connector block to the needle is shielded in order to avoid picking up noise and generating spurious needle excursions.

The complete interconnection diagram is shown in Appendix-B and technical specifications of hardware used are shown in Appendix-F.

SOFTWARE

The basic software system requirements for the development of prototype to be employed in testing can be summed up as:

- capability of acquiring real-time serial data from the GPS receiver at 9600 bps;
- capability of parsing the acquired data and processing the relevant fields to generate correction data on the fly;
- capability of providing Constant Track Made Good Mode for flying;
- capability of capturing waypoint position (Latitude and Longitude) when over flying it for the first time and storing them in a file for use in subsequent flights;
- using the waypoints, either captured or read from file, to generate heading correction commands either during interception or during tracking; and
- logging the necessary navigation data obtained from the GPS receiver in a data file along with the correction commands generated as well as the needle scale being used at the moment.

The navigation and data logging software for the test prototype was written in NI LabVIEW software. Use of a graphical programming language not only helped in reducing the software development time but also provided sufficient flexibility in designing graphical user interface with features like “button” controls as well as real-time position display. The pseudo-code of the LabVIEW software is provided in Appendix C.
COMPUTATION OF DTK-RNAV PARAMETER:

As mentioned earlier, this thesis is a proof of concept and not a complete implementation of the system. For small distances, using a flat earth model, the latitude-longitude system can be reasonably approximated as a Cartesian X-Y scale, with proper allowance made for distances away from equator.

![Diagram](image)

Figure 3. Calculating DTK using a flat earth model

From figure 3 above, the magnitude of angle made by the line joining the origin to the destination, from north can be given by:

\[
\text{Angle from north} = \arctan\left(\frac{(\text{destLon} - \text{orgLon}) \times \cos\left(\frac{\text{destLat} + \text{orgLat}}{2}\right)}{\text{destLat} - \text{orgLat}}\right)
\]
The cosine term in the equation provides allowance for the distance from the equator, as meridians converge towards the poles. However, in view of the idiosyncrasies of tangent of an angle, as it approaches 90°, as well as for computational accuracy, the abscissa and ordinate in the figure 3 can be swapped and the equation modified, yielding the same result, as shown below. Therefore, if the argument of arc tan in the equation above exceeds unity, i.e. (angle is greater than 45° and less than 90°), we have:

$$\text{Angle from north} = 90° - \arctan \left( \frac{(\text{destLat} - \text{orgLat})}{(\text{destLon} - \text{orgLon}) \times \cos \left( \frac{\text{destLat} + \text{orgLat}}{2} \right)} \right)$$

This angle from north (magnetic) can be called the DTK after making necessary allowance for the quadrant in which it is to be calculated by placing the FROM waypoint at the origin of the Cartesian system. For reasons of simplicity, the DTK computations were implemented only for western longitudes and northern latitudes.
CHAPTER V
DEVELOPMENT AND PRELIMINARY TESTING

The GPS receiver that was required for this thesis was borrowed from the Department of Human Factors and Systems, ERAU- Daytona Beach Campus for only a month. Thus, from the very beginning it was obvious that a GPS receiver simulator would also be required for the development of the processing software. However, no such simulator could be obtained from any source, including the GPS manufacturer and therefore, the development of the GPS receiver simulator software also became an integral part of the project. Since the LabVIEW software purchased by the department was licensed for use on a single computer, the only other alternative was to write the simulator program in the C language.

The simulator program had to be capable of providing a serial data interface exactly the same as that of the actual receiver. In order to reduce the complexity of the simulator, it was decided that Microsoft-Excel program would be used to generate the navigation data file for simulating the navigation data during various navigation maneuvers like interception and tracking with various aircraft turn rates. This data file would then be imported by the GPS receiver simulator program, which then would transmit it with suitable handshaking to the navigation/processing software running on a different computer via a serial port at an appropriate baud rate.
NEEDLE SENSITIVITY SCALE:

The prototype development also involved selecting appropriate display pointer needle sensitivity scales. This was an important system parameter, as it dictated the ease and accuracy with which the system could be used. The CDI unit was first bench calibrated for the drive voltages required to move the deviation bar along the ten-dot scale. The drive voltages required are shown in Table A1.

The two display sensitivity scales initially chosen were 1-2-3-4-5 and 1-2-3-6-9 for the five dots on each side, with ±20° being represented by full-scale deflections of opposite sides. The scale of 1-2-3-4-5 was chosen based on the ease of interpretation, whereas, the scale of 1-2-3-6-9 was chosen for anticipating roll out. The scaling equations used for the two scales are shown in Tables A2 and A3.

However, the recommendations of the flight crew after the first test flight resulted in replacing the 1-2-3-4-5 scale with that of 2-4-8-12-16, for use in the second test flight. This time, angles of ±30° magnitude were represented by full-scale deflections of opposite sides. Table A4 lists the scaling equations used in this case.

A variable resistor (wire wound potentiometer) of 20K ohm resistance was placed in series with the needle drive circuit in order to limit the current drawn by the meter movement coil and fine tune lateral bar positioning.
 TESTING:

Once the first version of the guidance software was ready, it had to be tested for performance. Developmental testing of the system comprised of stationary as well as mobile testing. Stationary testing involved tests of the system (GPS receiver, navigation computer, and the pointer display) with ‘live’ data obtained from GPS satellites to see if the software could run for extended periods of time while being interfaced with the GPS receiver and was capable of handling data discontinuities caused by momentary losses of signal. It also provided invaluable experience in efficiently handling possible problems like the Digital-to-Analog card becoming loose in the PCMCIA slot.

ROAD TESTS

The next stage of testing was that of mobile testing in a vehicle. This was necessary, as a stationary GPS receiver in the absence of translational velocity cannot provide meaningful track made good information. This mode of testing allowed a ‘live’ test of the system in a dynamic environment. In short, the road tests allowed evaluating that:

- The GPS receiver was also capable of operation in a vehicle with the antenna place inside the cabin.
- The system indeed worked satisfactorily on ground before commencing expensive flight tests.
• The magnitude of the tracking constant in the computation was appropriate for
good performance.

• The PCMCIA card was capable of remaining secure in its slot in the notebook
computer in the presence of moderate vibration.

The driving tests were designed to evaluate system performance for -

• Constant Track Made Good
• Tracking
• Interception

The test plans employed are included in the Appendix D.

CONSTANT TRACK MADE GOOD:

The algorithm for the Constant Track Made Good employs the difference of
the track made good and the desired track. This difference so obtained could also be
negative and therefore required appropriate handling. For e.g., if the DTK is 005° and
the TRK is 350°, the difference of the two is –345° which however, has to be
displayed as 15° clockwise. Thus, in one leg of the road test, the two road sections for
driving were so chosen that it resembled the above case.

Another case requiring special handling arises when the arithmetic difference
between the track made good and the desired track may not be the smallest
difference. This is on account of the fact that the compass scale is circular, i.e., it
transitions to 0° after 359°. Thus if the DTK is 290° and the TRK is 30°, the
difference for necessary correction should be 100° anti-clockwise and not 260° which the straightforward difference would indicate.

A driving test with DTK set to 350°, while driving on a road that provided a TRK of 20°, was used to test the above case. The magnitude of heading change commanded by the needle pointer was consistently 30° anti-clockwise. In the second case, the DTK was set to 20°, whereas the TRK driven was 345°. This time the magnitude of heading change commanded by the needle pointer was consistently 35° clockwise. The test results concurred with the anticipated values of track change required.

TRACKING:

The algorithm for tracking employs the magnitudes of cross track error as well as desired track. The correction displayed is the difference of the DTK angle and the appropriately weighted XTE. This difference can again possibly be negative and therefore has to be handled suitably. Thus, in one leg of the road test, the two road sections for driving were so chosen such that it resembled the above case.

However, limitations of remaining within the limits of road precluded the testing of tracking mode completely. This was because varying values of XTE resulted in steering commands that could not be followed in a car while remaining on the road. The test was therefore designed for driving on a stretch of road and evaluating if the steering commands generated were appropriate for the instantaneous values of XTE. Post-driving analyses of the test results confirmed that the steering commands generated were appropriate.
INTERCEPTION:

The algorithm for intercepting a desired track aims at achieving a heading that provides a TAE of ±40°. Thus, the computation involves subtracting 40° from the DTK if the XTE is positive, (i.e. the track lies to the left of the aircraft) and adding 40° to the DTK if the XTE is negative, (i.e. the track lies to the right of the aircraft). Again, appropriate corrections are required for ensuring that the required heading does not become negative or the heading correction does not exceed ±180°.

Since interception involves attaining a desired magnitude of TAE, the DTK values were selected by choosing waypoints separated by two miles on a straight stretch of road that also had at least one road intersecting it. The test, therefore involved driving on the intersecting road to have a cross track error of approximately 1.5 nm so that the system would enter interception mode. Driving towards the DTK would then command a steering correction that would provide a TAE of ±40°. The road did not provide the necessary geometry for exact interception angle and the correction demanded therefore, could not be made null while driving. However, analysis of post-drive test results confirmed that the steering commands displayed were indeed proper.

The road tests, therefore, not only provided an invaluable understanding of the system performance in a dynamic situation, but also gave substantial confidence in the system before commencing flight tests. Indeed, the many 'hiccups' that were encountered during the road tests aided in refining, and in some instances, modifying the software. One confounding problem, encountered during the early road tests, was
the erratic behavior of the system, whenever the car came to a stop. Investigation revealed that this problem involved the firmware in the GPS receiver. The version 1.2 firmware present in the receiver was not capable of providing 'position data' logs in the absence of 'translational velocity' i.e. motion. The problem was resolved only after a higher version (version 2.140) was obtained from the manufacturer and the firmware upgraded.

Another major 'bug' disinterred by road tests was the 'sign' of cross track error (+ or -). The GPS receiver's 'position data' logs did not provide the sign of XTE in the XTE field, nor did the accompanying manual clearly state this. The sign had to be extracted from a different field in the same navigation log and then assigned to the XTE. This problem was not evident in the first test where the XTE was actually positive and the system performed as anticipated, however, the next test with a negative XTE gave 'weird' results. The problem was positively identified and rectified with the assistance of the receiver manufacturer.
CHAPTER VI

FLIGHT TESTING

The final step in the development of the system was that of the flight tests. The flight tests had to be designed to demonstrate the system performance for all normal conditions. However, as this study was not a part of any funded research, the flight time had to be maintained at the minimum. As in the road tests, the flight tests had to evaluate system performance for the three navigation modes, including:

- constant track made good
- tracking
- interception

The planning for the tests included:

- safety of flight
- arranging for a suitable aircraft and pilots
- finding a suitable trial area,
- deciding flight paths to be used for flights, and
- choosing different angles of interception

SAFETY OF FLIGHT:

The flights were planned to operate only in VFR conditions for simplicity and safety. Precautions had to be exercised to offset the extra workload that the testing instrumentation could generate for the pilot. Since the testing area was a part of the flight training airspace around Prescott, a safety pilot was required to maintain a watch for traffic.
AIRCRAFT AND PILOTS:

The principal advisor for this research is also an FAA certificated flight instructor. He owns a Cessna 175 aircraft and graciously agreed to lend it for the flight tests and serve as the pilot in command. A second thesis advisor, who is also a professional aviator, consented to be the safety pilot for the flight tests.

TRIAL AREA:

The airspace around Prescott is a busy flight training area due to the location of Embry-Riddle Aeronautical University and a couple of other flight schools. The choice of a suitable trial area for flight tests was dictated by conflicting factors like the least 'commuting' time as well as low interfering traffic. A compromise between the two led to a trial area approximately 3 miles to the north of Paulden (10 miles to the north of Prescott). This area had a straight stretch of power lines that could be used as a ground reference as well as a ready check of navigation accuracy of the system. The area’s lack of tall vegetation cover also made marking waypoints easier as well as providing a reference to begin course reversal for the next leg.

FLIGHT PATH:

For reasons of economy, it was appropriate to test the constant track made good (CTMG) mode of the system, while on way to the trial area. It was soon evident that this choice was indeed proper. This not only helped in maintaining the flight time to a minimum, but also in evaluating each of the two implemented pointer-display needle sensitivities.
The desired track (DTK), for both interception as well as tracking was chosen as a straight stretch of the power lines with two physically distinct landmarks denoting the ‘TO’ and ‘FROM’ waypoints. The distance between the two waypoints was approximately seven nm, allowing approximately 3:30 minutes of tracking at a cruise speed of 120 Knots. On the completion of a test leg that included interception, tracking, and course reversal, the TO and FROM waypoints could be interchanged, therefore providing a new leg without wasting flight time.

INTERCEPT ANGLES:

The leg runs during the flight tests provided both left and right values of XTE for interception and tracking. On completion of tracking for a leg, the aircraft was flown outbound on an appropriate track for course reversal as well as achieving an XTE of approximately 2 nm for the next interception. This value of 2 nm, provided sufficient lengths of ground tracks for evaluating the quality of interception. Thus, properly chosen left and right hand turns, after tracking, provided the necessary positioning before commencing the interception for the next run. The course reversals also positioned the aircraft with an initial track angle error of about 40°, which was to be reduced to an acceptable value, while following the needle pointer’s commanded correction during interception.
ANALYSIS OF THE FIRST FLIGHT TEST

After take-off, the aircraft was initially flown to provide a CTMG of 348° for approximately 4 minutes with a needle scale of 1-2-3-4-5, while proceeding to the trial area. During this period, the pilot-in-command tried to keep the pointer needle centered as far as possible, except occasionally evaluating the sensitivity of the needle by deliberate momentary heading shifts.

The pilots found the 1-2-3-4-5 scale to be extra sensitive, requiring constant control input for maintaining zero position of the pointer needle. They opined that this scale could have perhaps been appropriate for approach phases of flight where a precise control of flight path is necessary, but for enroute phases, it appeared to be excessively demanding.
From the position plot as shown in Figure 4 above, the ground track appears to be remarkably straight over the stretch for which CTMG mode had been used. This demonstrated that the steering algorithm was effective in this mode.

For the first flight test, the system had been configured for a threshold XTE value of 1.5 nm to effect a switchover from interception mode to tracking. The live
Figure 5. Ground tracks of the first flight in tracking and interception mode

position plot on the navigation-cum-data logging computer as well as post flight analysis of test data, revealed that the interception of the desired track was too shallow. This resulted from the fact that once the aircraft crossed the 1.5 nm XTE threshold, the tracking mode took over, as designed. The tracking algorithm then provided the steering commands that tried to gently maneuver the aircraft on to the desired track instead of providing a well-defined intercept. The shallow intercepts are clearly visible in the ground track plots of Figure 5 above.
Yet, another observation made during the three tracking legs was that of excessive pilot input requirement. This resulted from the use of a larger value of the weighting constant for XTE compensation, in the tracking correction computation. With the commanded correction being directly proportional to the weighted XTE, a reduced value of the weighting constant needed to be employed in the second flight test.

ANALYSIS OF THE SECOND FLIGHT TEST

The second test flight was flown with the first needle scale (1-2-3-4-5) modified to 2-4-8-12-16, while the second scale of 1-2-3-6-9 remained unchanged. Both scales were tested on the way to the trial area. The aircraft was first flown to provide a CTMG of 290° for 5 minutes with a needle scale of 2-4-8-12-16 and then the track was changed to 047° for the next 5 minutes with a needle scale of 1-2-3-6-9. In both the cases, the pilot-in-command tried to keep the pointer needle centered, except occasionally evaluating the sensitivity of the needle by deliberate momentary heading shifts, as in the first test.
From the position plot in Figure 6 below, the ground tracks appear to be remarkably straight over each of the stretches of constant TMG. The pilots noted that the 2-4-8-12-16 scale was significantly less demanding for maintaining a constant track, than the 1-2-3-6-9 scale, and therefore decided to use it alone for the ensuing legs of the tracking and interception.

*Figure 6. Ground track of the second test flight in CTMG mode*
The algorithm for tracking had been modified after the first flight, in an attempt to produce a well defined intercept. The transition value of XTE was accordingly reduced to 0.5 nm from 1.5 nm. Live position plot as well as post flight data analysis, this time did display a sharper intercept than the previous flight.

Figure 7. Ground tracks of the second test flight in tracking and interception mode

The ground tracks made by the aircraft during the interception and tracking legs are shown in Figure 7 above, where well-defined intercepts can clearly be seen. This figure also shows clearly repeated ground tracks during tracking, testifying to
the effectiveness of the system. In fact, the analysis of the logged-data file from the flight test indicates that the XTE had been contained to one hundredth of a nautical mile during tracking for significant durations.

One problem that was observed this time was that of needle swings during the transition from interception phase to tracking. The algorithms employed during the two phases of flight were different and no provisions had been made to provide for a 'graceful' transition from interception to tracking. This sudden transition between two different algorithms at the threshold values of XTE resulted in sharp movement of needle pointer.

The weighting constant in the tracking algorithm for the second flight had been reduced by about 20 percent (from 2800 earlier to 2400) to prevent needle correction commands from being too sensitive to minor inadvertent deviations from the DTK.

LIMITATIONS:

The DTK (for evaluating the tracking and interception performance of the system) had been chosen to coincide with a highly conspicuous terrain feature (a straight stretch of power lines), so as to provide a ready reference for judging the navigation accuracy. Therefore, it can be argued that the presence of a distinct visual reference could have subconsciously influenced the flying.

On the other hand, being able to maintain a XTE of 0.01nm or less consistently for significant durations (up to 100 seconds at a stretch), when flying at 120 knots speed while being 1000 ft above ground level, cannot entirely be
accounted for by visual flying alone. From basic trigonometric identity, a 60 ft (0.01 nm) deviation at distance of 1000 ft subtends an angle of about 3.4° at the eye. It seems unlikely that a precision of this order can be maintained for this long by manual proportional control alone based on sight.

Figure 8. XTE trend during tracking for the three Legs

Figure 8 above, a plot of XTE for each of the three legs of tracking, as the aircraft XTE settles to a value less than 0.08 nm after interception, shows that on two of the legs the XTE is maintained within 0.01nm for significant period of time. The swings outside the bands are due to deliberate pilot control inputs for evaluating the performance of the system.
The needle display had been mounted on top of the instrument panel of the aircraft in front of the right seat, but was turned at an angle so as to be visible for the PIC in the left seat. It is noteworthy that despite its not being within the primary scan field of the pilot flying, significant precision was achieved.
CHAPTER VII
CONCLUSION AND RECOMMENDATIONS

The idea of producing an affordable, but precise lateral-navigation flight director based on the GPS for the benefit of the aviation community, especially general aviation, culminated in this research. This research, accordingly, focused on evaluating the feasibility of using a new type of guidance system to be used in aircraft and demonstrated that the proposed concept does in fact hold promise, and therefore merits further development. The thrust of this study was directed at realizing a prototype of the proposed guidance system and subjecting it to initial flight-testing.

The navigation parameters used in the algorithms in the proposed system are readily available from all navigation grade GPS receivers. With the trend of equipping aircraft with GPS receivers being on the upswing, a major part of the cost of proposed system has been already defrayed. The additions now involved are a minor calculation overhead for calculating the heading correction commands and investigating an appropriate display for conveying the correction information to the flight crew.

Despite the fact that the prototype system did not employ the differential positioning mode of the GPS, remarkable accuracy in navigation was still evident. Now with the wide-area augmentation system (WAAS) becoming fairly common in use, there is no doubt that an even higher accuracy can be realized with the same system. Thus, the task of commercially implementing this concept after necessary certification deserves serious priority.
RECOMMENDATIONS:

1) The algorithm needs to be modified to provide for a graceful transition between interception and tracking, in order to prevent needle swings during the transition between the two phases of flight.

2) The testing in this research had been performed in VFR conditions but the system's performance also needs to be evaluated for IFR. This is necessary in order to evaluate the flight path accuracy and pilot's acceptance of this type of guidance, when the pilot's workload increases due to instrument flight conditions.

3) In this research, the CDI bar was used for displaying the heading correction commands. The ten-dot scale of the deviation bar had been calibrated for use with different sensitivities. However, no consideration was given to the human factor issues of presentation of this type of data owing to the 'proof of concept' only nature of the research. Thus, further studies are necessary to find an optimal display for this system's development.

4) Proper placement of the display mentioned in recommendation 3 above, within the instrument scan area of the pilot, also merits further research. For IFR operations, the GPS steering information must be integrated with other displayed flight data. However, the correction information displayed during flight tests was readily used in VFR conditions, even when the display was located on top of the instrument panel in front of the right seat.
REFERENCES


Table 1. CDI Needle Deflection Sensitivity

<table>
<thead>
<tr>
<th>Deflection from Center (dots)</th>
<th>Voltage required&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>±1 (inner circle)</td>
<td>±0.60 V</td>
</tr>
<tr>
<td>±2</td>
<td>±1.25 V</td>
</tr>
<tr>
<td>±3</td>
<td>±1.75 V</td>
</tr>
<tr>
<td>±4</td>
<td>±2.25 V</td>
</tr>
<tr>
<td>±5</td>
<td>±2.75 V</td>
</tr>
<tr>
<td>±Full scale</td>
<td>±3.55 V</td>
</tr>
</tbody>
</table>

<sup>a</sup> = no scaling used

Table 2. Piece-wise linear scales used for the steering correction angles, Scale used 1-2-3-4-5

<table>
<thead>
<tr>
<th>Input angle range (+ range shown)</th>
<th>Equation for scale used</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>Y=0.6*X</td>
</tr>
<tr>
<td>1-2</td>
<td>Y=0.65X-0.05</td>
</tr>
<tr>
<td>2-3</td>
<td>Y=(0.5X+0.25)</td>
</tr>
<tr>
<td>3-4</td>
<td>Y=(0.5X+0.25)</td>
</tr>
<tr>
<td>4-5</td>
<td>Y=(0.5X+0.25)</td>
</tr>
<tr>
<td>5-20</td>
<td>Y=(0.8X+37.25)/15.0</td>
</tr>
</tbody>
</table>

*Note.* only equations for positive values shown
Table 3. Piece-wise linear scales used for the steering connection angles, Scale used 1-2-3-6-9

<table>
<thead>
<tr>
<th>Input angle range (+ range shown)</th>
<th>Equation for scale used</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>Y=0.6*X</td>
</tr>
<tr>
<td>1-2</td>
<td>Y=0.65X-0.05</td>
</tr>
<tr>
<td>2-3</td>
<td>Y=0.5X+0.25</td>
</tr>
<tr>
<td>3-6</td>
<td>Y=(0.5X+3.75)/3.0</td>
</tr>
<tr>
<td>6-9</td>
<td>Y=(0.5X+3.75)/3.0</td>
</tr>
<tr>
<td>9-20</td>
<td>Y=(0.8X+23.05)/11.0</td>
</tr>
</tbody>
</table>

Note. only equations for positive values shown

Table 4. Piece-wise linear scales used for the steering connection angles, Scale used 2-4-8-12-16

<table>
<thead>
<tr>
<th>Input angle range (+ range shown)</th>
<th>Equation for scale used</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>Y=0.3X</td>
</tr>
<tr>
<td>2-4</td>
<td>Y=(0.65X-0.1)/2.0</td>
</tr>
<tr>
<td>4-8</td>
<td>Y=(0.5X+3.0)/4.0</td>
</tr>
<tr>
<td>8-12</td>
<td>Y=(0.5X+3.0)/4.0</td>
</tr>
<tr>
<td>12-16</td>
<td>Y=(0.5X+3.0)/4.0</td>
</tr>
<tr>
<td>16-30</td>
<td>Y=(0.8X+25.7)/14.0</td>
</tr>
</tbody>
</table>

Note. only equations for positive values shown
APPENDIX-B

INTER-CONNECTION DIAGRAM OF THE SYSTEM

Bendix-King GPS Antenna

RG-400 Coax-Cable

NovaTel GPS Receiver

TNC Antenna Connector

Notebook Computer

Serial Port DB-9

Null Modem Cable

COM3 Port

Power Connector

DC Power Cable

PCMCIA DAQCARD AO-2DC

Ribbon Cable

Pin 20 & 21

CB-27 Connector Block

Rechargeable Battery

Twin Core Shielded Cable

Pin 1 & 2

DB-25 Connector

CDI Display
APPENDIX- C

PSEUDO-CODE FOR THE SOFTWARE

Note. - Parentheses () enclose COMMENTS

- MODULES and SUB-MODULES are part of main LabVIEW VI
- SUBVIs are separate LabVIEW modules
- VIs (Virtual Instrument) in LabVIEW are the complete modules that can be individually tested
  (similar to subroutines in text based programming)

main VI start

initialize system

loop until user commands to stops
  read and process data
  display and store data
  navigate next leg
  display error message from error stream on computer display

shutdown

main VI end
MODULE initialize system

get file name for logging data
write header information in file
initialize indicators
initialize serial port
initialize DA card and set output to zero

loop until GPS receiver is available on serial port
try three times
    command GPS receiver for air or land operation (DYNAMICS CMD)
    if not accepted on third or before, exit with error message

get navigation mode selection (Constant TMG or Tracking & Interception)
if navigation mode is "Constant Track Made Good"
    get heading to fly
    set FROM waypoint to dummy-1 coordinates
    set TO waypoint to dummy-2 coordinates (dummy-1 and dummy-2 coordinates should differ by about 1° in both lat. and lon.)
else navigation mode is "Tracking & Interception"
    get WPT_choice (capture WPT from GPS or read WPT from file)
    if WPT_choice is "Read WPT from file"
        read waypoint file
    else WPT_choice is "Capture WPT from GPS"
        capture WPTs
    read waypoint sequence for first leg
    assign TO and FROM waypoints for Active Leg

wait for commencing navigation (Separate SUBVI)
set scale for the live position plot

assign active waypoints to GPS receiver for navigation (Separate SUBVI)
if not accepted, exit with error message
else flash "Command Accepted LED" for 5 seconds

command GPS receiver to begin sending 'position data' (LOG GPRMB CMD)
if not accepted, exit with error message

command GPS receiver to begin sending 'navigation data' (LOG GPRMC CMD)
loop until accepted response is received

END initialize system
MODULE read and process data

wait until 'position data' log is valid (log length >70 chars)
read 'position data' log
strip data fields from 'position log'
read 'navigation data' log
strip data fields from 'navigation data' log

check if 'logged data' is valid in both logs
if 'logged data' is invalid, flash "Data Invalid" LED on display, continue

convert the 'present Lat./Lon. data' from ddmm.mm format to dd.dd
append present position coordinates to the position display array
refresh position plot on display

if ground speed is less than 10 kts., inject pre-determined code in error stream

check for screen button status change (SUB MODULE)
calculate HDG correction
calculate scaled voltage from 'HDG correction' for driving needle pointer

END read and process data

MODULE display and store data

check for presence of DA card
if DA card is absent, flash "CHECK DA CARD" LED on display, continue
if ground speed is more than 10 kts. and DA card is present, output scaled -voltage to DA card

fill data array with necessary fields from above logs and computations
convert data array to spreadsheet string
write spreadsheet string to data file

END display and store data

MODULE navigate next leg

if perpendicular to destination WPT has been passed and route has 3 waypoints
change TO and FROM WPTs in global variables for next leg
assign active waypoints to GPS receiver for navigation (Separate SUBVI)
if accepted, flash "Command Accepted LED" for 5 seconds
else continue

check if user wants to change navigation leg (CHANGE NAVIGATION LEG button)
if confirmed
change nav leg (SUB MODULE)
remove injected code from error stream
assign active waypoints to GPS receiver for navigation (Separate SUBVI)
if accepted, flash "Command Accepted LED" for 5 seconds
else continue

END navigate next leg
MODULE shutdown

  close data file
  command receiver to stop logging data (UNLOG GPRMB & GPRMC)
  release serial port
  display exit status

END shutdown

SUB MODULE change nav leg (In program this is a part of main VI)

  ask user to confirm changing navigation leg
  if confirmed
    if navigation mode is "constant track made good"
      read new HDG to fly
    else
      if number of WPTS is 2
        swap TO and FROM waypoints in global variables
      else
        change TO and FROM waypoints in global variables for reversed legs
    else continue
  else continue

END change nav leg

SUB MODULE check for screen button status change

  if "STOP LOGGING" button is depressed exit main loop
    if "SCALE SENSITIVITY" button is depressed toggle needle scale sensitivity
    else continue
  else continue

END check for screen button status change

SUBVI read waypoint file

  loop until user accepts the route
    get file name to read waypoints
    read file contents and display to user for verification
    ask user to confirm his choice of route

  initialize the global Lat./Lon. variables with WPT co-ordinates & ID from file

END read waypoint file
SUBVI capture WPTs

get route name
get number of waypoints in route
get position (Separate SUBVI)

END capture WPTS

SUBVI get position

read file name to store route and waypoint information
read route name and number of waypoints
command GPS receiver to send precise position logs (LOG GPGGARTK CMD)
try 25 times
check for command acceptance from GPS receiver
if not accepted on 25th attempt or before, exit with error message

loop for 'number of waypoints' in route times
if "Position Valid" LED is ON and "Capture Waypoint Button" is depressed
read waypoint ID
write waypoint ID and position co-ordinates to file
initialize the global Lat./Lon. variables with WPT co-ordinates & ID
else continue

command GPS receiver to stop sending precise position logs (UNLOG -GPGGARTK CMD)

END get position

SUBVI assign active waypoints to GPS receiver for navigation

use TO-FROM waypoints to compute DTK for active leg
draw desired track on position plot (Separate SUBVI)
assemble necessary command parameters from global variables
send 'activate navigation' command to GPS receiver (SETNAV CMD)
try three times
read response from GPS receiver
if not accepted on third or before, exit with error message

END assign active waypoints to GPS receiver for navigation

SUBVI wait for commencing navigation

ask user to confirm commencing navigation
wait until confirmed

END wait for commencing navigation
SUBVI read waypoint sequence for first leg

get user choice of first leg (1-2 or 2-1 for 2 WPTs / 1-2-3 or 3-2-1 for 3 WPTs)

END read waypoint sequence for first leg

SUBVI draw desired track on position plot

initialize New_X-position[0] with FROM longitude
initialize New_Y-position[0] with FROM latitude
initialize delta

loop until New_X-position is less than TO Longitude or New_Y-position is less than TO -Latitude or loop count is less than 5000

(suitably modified for appropriate quadrant)

New_Y-position[i+1]= New_Y-position[i]+delta*tan(DTK)
New_X-position[i+1]= New_X-position[i]+delta

END draw track
APPENDIX- D

ROAD TESTS PLANS

Tests were performed to judge system performance for:

a) Ability to maintain a constant given course;

b) Ability to track a given course;

c) Ability to intercept a given course; and

d) Ability to track a route with two legs;

a) Steps to be followed

1. Turn on the GPS receiver and place the GPS antenna in a position that ensures continuous satellite visibility. Once the ‘Position Valid’ LED comes on the receiver, start the LabVIEW based processing software by double clicking the ‘Master Program’ icon in the Latest folder on the desktop.

2. Make sure “LAND” vehicle mode is selected on the program front panel. Run the software by clicking the white arrow near the top left corner of the application window.

3. Drive to the Rummel –Willow Creek intersection (ERAU secondary entrance), enter a suitable file name for the log, and after activating Constant Heading Navigation, select a heading of $350^0$ and click OK.

4. After clicking OK at “Commence Navigation” prompt, drive northwards on the Willow Creek Rd. to the Willow Creek-Chino Valley Hwy intersection.
Full-scale deflection to turn towards left should appear on the needle display (about $30^\circ$ on the computer display).

5. Upon reaching the Willow Creek Rd and Chino Valley Hwy intersection, click on the “Change Navigation Leg” button and after confirming with OK when prompted, enter $165^0$ as the new heading. Drive southwards on the Chino Valley Hwy for approximately 2 miles. No significant movement in the needle should be seen.

6. Reverse the car to point northwards. Click “Change Navigation Leg” Button and after confirming with “OK” when prompted, enter $20^0$ as the new heading. Drive northwards towards the Willow Creek Rd and Chino Valley Hwy intersection. Full-scale deflection to turn right should appear on the needle pointer (about $35^0$ on the computer display).

7. On reaching Willow Creek Rd and Chino Valley Hwy intersection click “Change Navigation Leg” button and after confirming with “OK” when prompted, enter $200^0$ as the new heading. Now head southwards towards ERAU. No significant deflection should be seen.

8. On reaching ERAU main entrance, click “Stop Logging”. Make a copy of the logged data file and keep it safely.
b) Steps to be followed

1. Ready system as above.

2. Run the main software by clicking on the white arrow near the top left corner of the application window.
   - Enter file name for logging navigation data.
   - Select “Tracking and Interception” when the “Enter Navigation mode” dialog appears.
   - Enter a meaningful name for the route to be driven and the number of WPTs –2 here and click OK.
   - Enter the file name for storing WPT data and click OK.

3. Once the Position Valid LED on the computer screen comes ON, drive to the ERAU Main entrance, capture its position, and enter ERU for the WPT name.

4. Proceed to the Willow Creek Rd. and Chino Valley Hwy intersection, capture its position, and enter CVH for the WPT name.

5. When prompted for “Navigation Leg”, select CVH-->ERU. Now the active route is CVH->ERU.

6. Click OK when “Commence Navigation” prompt appears and drive down the Chino Valley Hwy towards Watson Lake Park and then down Willow Lake Rd to ERAU Main entrance (ERU). Initially the heading correction should display a turn right (+) indication and the magnitude should remain at full right deflection until the Watson Lake Park intersection. After the right turn on Watson Lake Park intersection towards the Willow Lake Road, the needle should change to full scale turn left (-) indication.
When Willow Creek Road-Willow Lake Rd intersection is reached, click on "Change Navigation Leg" and click OK when asked to confirm intention.

Now the active Route is ERU⇒CVH.

7. Drive down Willow Creek Rd to ERAU Main entrance. There should not be any significant correction required after passing by Ford car dealership.

8. Click "Stop logging" at ERAU Main entrance.
c) Steps to be followed

1. Same as b) above for system setup. **FOR 2 WPTS**

2. Setup the system for "Tracking and Interception" as before, drive to the ERAU Main entrance, and capture it as ERU.

3. Then proceed to the Willow Creek Rd. and Chino Valley Hwy intersection and capture it as CVI.

4. When prompted for "Navigation Leg", select ERU-CVI. Now the active route is ERU⇒CVI.

5. Drive southwards on the Chino Valley Hwy (southwards) to Phippen Museum. Turn northwards and click OK on "Commence Navigation" prompt. Now drive northwards to the Willow Creek Rd. and Chino Valley Hwy intersection (CVI). Full-scale deflection to turn right should appear on the display. Even after crossing the WPT-2 and heading further north on Hwy 89 the full deflection to right will remain. Drive approximately 2 miles further north from CVI before turning back.

6. Turn back and click on the "Change Nav Leg" button and drive towards ERAU. The display will initially indicate turn left indication, which will decrease to a right turn deflection as the CVI intersection approaches. After turning left at the CVI, travel on the Willow Creek Rd. towards ERAU. The display should show not show significant deflection ($0^\circ$).

7. Click "Stop Logging".
d) Steps to be followed

1. Same as b) above except enter 3 WPTs.

2. Setup the system for “Tracking and Interception” as before, drive to the ERAU Main entrance, and capture its position as ERU.

3. Proceed to the Willow Creek Rd. and Chino Valley Hwy intersection and capture its position as CVI.

4. At the Chino Valley Hwy intersection, take a left turn and proceed North on the CV Hwy for approximately 2 miles and capture the third waypoint location as CVA.

5. When prompted for “Navigation Leg”, select ERU-CVI-CVA. Now the active route is ERU⇒CVI⇒CVA. Next, reverse the car and drive back to ERAU Main entrance.

6. Click OK for the Commence Navigation prompt and drive northwards to the Chino Valley Hwy intersection. Now with the active leg ERU⇒CVI, little or no needle deflection should be seen.

7. At the intersection, turn left northwards and drive towards Chino Valley. With an active leg now automatically changed to CVI⇒CVA, insignificant correction (0°) should appear on the display. Drive approximately 2 miles before turning back.

8. Click Change Nav. Leg after reversing car to face southwards. Now the active route is CVA⇒CVI⇒ERU. Confirm with OK and proceed southwards towards the Chino Valley Hwy intersection. With active leg
**CVA⇒CVI** little or no deflection should be seen. At the Chino Valley Hwy intersection, turn right to and travel southwards towards ERAU Main entrance. Still little or no deflection should be seen with the active leg now being CVI⇒ERU.

9. Click “Stop Logging”. 
APPENDIX E

FLIGHT TEST PLANS AND REPORTS
FLIGHT TEST PLAN (First Flight)

OBJECTIVE: Capture Waypoints Flight

- Depart KPRC northbound, climb to 6300'
- Fly Track Made Good of 348° by needle for 5 minutes while evaluating its performance.
- Callout "Preparing to over-fly ALP"
- Over-fly ALP and callout when overhead.
- Track power-lines to BRV (TRK 023°) and callout when overhead.
- Fly outbound for 1 minute before turning left to make course reversal.
- Callout "Ready for First Tracking".

(34-52.8N, 112-25.5W)

Constant Track Made Good (HDG 348°) for 5 minutes
OBJECTIVE: Initial Tracking with Course reversal over ALP

Needle Sensitivity 1-2-3-4-5

- When over BRV, begin tracking leg BRV-ALP with the Needle Pointer.
- Observe the performance of the system.
- Visually confirm crossing ALP and continue tracking the extended leg for 1 minute.
- Turn right to HDG 233°
- Track outbound for 1 minute, turn left to HDG 053°
- Callout "Ready for Intercepting ALP-BRV"
OBJECTIVE: Interception and Tracking with Needle pointer

Needle Sensitivity 1-2-3-6-9

- Intercept extended centerline of leg ALP-BRV outside of ALP using Needle Pointer.
- Track the leg ALP-BRV using Needle Pointer. Continue observing the performance of the system.
- Visually confirm crossing BRV and continue tracking the extended leg for 1 minute.
- Turn left to HDG 353°.
- Track outbound for 1 minute.
- Make right turn to HDG 173°.
- Callout "Ready for Intercepting BRV-ALP"
OBJECTIVE: Interception and Tracking with Needle Pointer

**Needle Sensitivity 1-2-3-4-5**

- Intercept extended centerline of leg BRV-ALP outside of BRV with Needle Pointer.
- Track the leg BRV-ALP with Needle Pointer and note system performance.
- Visually confirm crossing ALP and continue tracking the extended leg for 1 minute.
- Head back to the airport
Report of the First Test Flight of the New Guidance Algorithm
03-09-2004

The flight tests started with a preflight safety brief by Dr. Wischmeyer, who was to be the pilot-in-command to safety pilot Jeff Kotson and researcher Mukul Mishra. Dr. Wischmeyer preflighted the aircraft while Jeff Kotson strapped the GPS antenna to the aircraft instrument panel along with the needle pointer display. The Needle display was taped such that it provided the subject pilot (in left seat) with sufficient visibility at the same time remaining visible to the safety pilot.

The data-logging and processing laptop notebook was placed in the rear right seat so as to allow the DA card cable to stay unhindered from the upholstery in order to prevent inadvertent movement due to contact. The necessary cable connections were made and the system was ready for the first test flight.

After receiving clearance for takeoff from Prescott Tower, the flight piloted by the subject pilot, climbed to 6300’ heading southwest initially before turning north with constant track made good of 348°. After flying for 4 minutes, the track made good was changed to 005° to arrive at the designated trial area near Paulden. The pilots noted that the needle appeared to be quite sensitive about the zero position for sensitivity of 1-2-3-4-5.

The system was readied for capturing the Waypoints to be used in subsequent test flights. The first Waypoint Alpha (ALP) was captured where the power lines made a 30° right turn. The aircraft proceeded on a HDG of 020° to arrive at the second Waypoint Bravo (BRV) near the intersection of power lines and railroad tracks for capturing its location.

The flight proceeded on the outbound heading of 020° from BRV for 1 minute before turning right to HDG of 065° for 1 minute. After a left turn for making a course reversal the aircraft was established on a HDG of 245°. At this point the Needle pointer was made available to enable tracking the leg BRV-ALP.
TRACKING BRV-ALP:

The tracking was performed at the Needle sensitivity of 1-2-3-4-5 and again the subject pilot noted that the needle appeared too sensitive about zero position causing guidance commands with excessive bandwidth. The cross track sensitivity appeared to be high, appropriate for approach but not enroute phase. After crossing ALP, the flight tracked the extended leg for 1 minute as per the test plan before turning right to HDG of 233°. The flight tracked outbound on HDG 233° for 1 minute, before turning left to HDG 053°.

INTERCEPTING and TRACKING ALP-BRV:

When the pilot called out “Ready for intercepting ALP-BRV” after leveling out from the turn, the active navigation leg was changed to ALP-BRV. The Needle pointer, now with a sensitivity of 1-2-3-6-9 then commanded the required the heading change necessary first for intercepting the leg and then tracking it. The intercept appeared shallow, switching to tracking mode at a XTRK of 1.5 NM. After confirming having crossed the BRV Waypoint from the Computer display, the flight proceed to track the extended leg of ALP-BRV for 1 minute, before commencing course reversal for the next intercept.

INTERCEPTING and TRACKING BRV-ALP:

When the pilot called out “Ready for intercepting BRV-ALP” after leveling out from the right turn, the active navigation leg of the system was changed to BRV-ALP. The Needle pointer, now with a sensitivity of 1-2-3-4-5 then commanded the required the heading change necessary first for intercepting the leg and then tracking it. This intercept too appeared smooth but shallow, switching to tracking mode at a XTRK of 1.5 NM. As earlier the pilots noted that the Needle sensitivity was excessive about zero. After confirming having crossed the ALP Waypoint from the computer display, the flight headed back to the airport.
Pilot recommendation after first flight:

- The cross track performance was OK for approach phase but was too sensitive for en-route phase
- The different sensitivity scale should be tried on next flight
  The transition from interception mode to tracking is too early at 1.5 nm and should be reduced suitably, to approximately 0.5nm
FLIGHT TEST PLAN (Second Flight)

OBJECTIVE: Capture Waypoints Flight

- Depart KPRC northbound, climb to 6300'
- Fly Track Made Good of 290° by needle for 5 minutes while evaluating its performance.
- Fly Track Made Good of 047° by needle for next 5 minutes while evaluating its performance.
- Callout "Preparing to over-fly ALP"
- Over-fly ALP and callout when overhead.
- Track power-lines to BRV (TRK 023°) and callout when overhead.
- Fly outbound for 1 minute before turning left to make course reversal.
- Callout "Ready for First Tracking".
OBJECTIVE: Initial Tracking with Course reversal over ALP
Needle Sensitivity 2-4-8-12-16

- When over BRV, begin tracking leg BRV-ALP with the Needle Pointer.
- Observe the performance of the system.
- Visually confirm crossing ALP and continue tracking the extended leg for 1 minute.
- Turn right to HDG 233°
- Track outbound for 1 minute, turn left to HDG 053°
- Callout "Ready for Intercepting ALP-BRV"
**OBJECTIVE:** Interception and Tracking with Needle pointer

*Needle Sensitivity 2-4-8-12-16*

- Intercept extended centerline of leg ALP-BRV outside of ALP using Needle Pointer.
- Track the leg ALP-BRV using Needle Pointer. Continue observing the performance of the system.
- Visually confirm crossing BRV and continue tracking the extended leg for 1 minute.
- Turn left to HDG 353°.
- Track outbound for 1 minute.
- Make right turn to HDG 173°.
- Callout "Ready for Intercepting BRV-ALP"
OBJECTIVE: Interception and Tracking with Needle Pointer

**Needle Sensitivity 2-4-8-12-16**

- Intercept extended centerline of leg BRV-ALP outside of BRV with Needle Pointer.
- Track the leg BRV-ALP with Needle Pointer and note system performance.
- Visually confirm crossing ALP and continue tracking the extended leg for 1 minute.
- Head back to the airport

03-10-2004

The flight tests commenced with a preflight safety brief by Dr. Wischmeyer, who was to be the PIC to safety pilot Jeff Kotson and researcher Mukul Mishra. Dr. Wischmeyer preflighted the aircraft while Jeff Kotson strapped the GPS antenna on the aircraft instrument panel along with the Needle pointer display. The Needle display was taped such that it provided the subject pilot (in left seat) with sufficient visibility at the same time remaining visible to the safety pilot. The necessary cable connections were made and the system was ready for the second test flight.

After receiving clearance for takeoff from Prescott Tower, the aircraft, climbed to 6600', heading southwest initially before turning north with constant track made good of 290° with the display sensitivity of 1-2-3-6-9. One minute after takeoff, the DA card alarm on the computer monitor came on, indicating that the DA card had become loose. The vibrations resulting from engine full power during takeoff probably caused it. The navigation program was stopped and the card reinserted. After a quick reconfiguration with appropriate utility, the navigation program was restarted with the constant track made good of 290°. This time the card remained secure for the entire duration of the flight (it was held by the researcher as a precaution). After flying for 5 minutes, the desired track made good was changed to 047° with the display sensitivity now changed to 2-4-8-12-16 to arrive near the designated trial area near Paulden. The pilots noted that the needle sensitivity appeared to be appropriate when set to 2-4-8-12-16, unlike the previous scale (1-2-3-4-5), which seemed to have excess bandwidth requiring excessive pilot input.

The system was readied for capturing the waypoints to be used in subsequent test flights as the flight descended to 6300'. The first waypoint, Alpha (ALP), was captured at the extended leg of the power lines, near a house. The aircraft proceeded along the power lines to arrive at the second waypoint, Bravo, (BRV), near the intersection of power lines and railroad tracks for capturing its location.
The flight proceeded on the outbound heading of approximately 020° from BRV for 1 minute before turning right to HDG of 065° for 1 minute. After a left turn for making a course reversal the aircraft was established on a HDG of 245°. At this point the Needle pointer was made available to enable tracking the leg BRV-ALP.

**TRACKING BRV-ALP:**

The tracking was performed at the Needle sensitivity of 2-4-8-12-16 and again the pilot flying noted that the transition from interception to tracking was jerky and needed proper smoothing. After crossing ALP, the flight tracked the extended leg for 1 minute as per the test plan before turning right to HDG of 233° to make a course reversal in preparation for the next intercept.

**INTERCEPTING and TRACKING ALP-BRV:**

When the pilot called out “Ready for intercepting ALP-BRV” after leveling out from the turn, the active navigation leg was changed to ALP-BRV. The Needle pointer, still with a sensitivity of 2-4-8-12-16, then commanded the required heading change necessary for intercepting of the leg. The switch over from intercept to tracking mode was now made at an XTE of 0.5 NM. After visually confirming having crossed the BRV Waypoint, the flight proceeded to track the extended leg of ALP-BRV for 1 minute before commencing the course reversal for the next intercept.

**INTERCEPTING and TRACKING BRV-ALP:**

When the pilot called out “Ready for intercepting BRV-ALP”, after leveling out from the right turn, the active navigation leg of the system was changed to BRV-ALP. The Needle pointer, still with a sensitivity of 2-4-8-12-16, commanded the required the heading change necessary for intercepting and tracking the leg. This intercept appeared sharp switching to tracking mode at a XTE of 0.5 NM. After tracking the leg for about 3:30 minutes and confirming the aircraft crossed the ALP Waypoint visually, the flight headed back to the airport.
Pilot recommendation after second flight:

- The Needle scale of 2-4-8-16-30 seems appropriate for approach.
- However, for the en-route portion of flights, a scale of 3-6-9-12-15 might be a better alternative to reduce pilot workload.
- There should preferably be a dead band for certain amount of cross track excursions from DTK centerline before requiring pilot intervention.
- The dead band should also apply to certain HDG excursions.
- The algorithm should be modified to provide a graceful switchover from interception to tracking mode.
APPENDIX- F

GPS antenna:

  BENDIX/KING KA 92 Antenna,
  GPS L1 Active,
  P/N 071-01553-0200

GPS receiver:

  Novatel OEM-4 Receiver

GPS antenna connector cable:

  M17/128 - RG400, MIL-C-17G, 12814 THERMAX RGS-400

CDI display:

  Aircraft Radio and Control,
  Converter Indicator, IN-386A,
  PN 46860-2000

Analog output card:

  National Instruments DAQCard -AO-2DC
  Low cost analog output with current loop (Type II PCMCIA card), with 2
  voltage output channels (12 bit resolution, ±5, 0-10V software selectable
  range)

Computer:

  DELL 8600 Inspiron notebook Pentium® M Processors at 1.40GHz,

Battery for GPS receiver:

  Power Wheels by Fischer-Price, 12 Volt, 9.5-Ampere Hour, and Rechargeable
  Type 12V Battery 00801-0638