Modeling GPS Receiver Performance In Civil Aviation Trajectories Using Current GPS Constellation Performance

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BIOGRAPHY

Patricia Seward received her BS in Electrical Engineering from New Mexico Institute of Mining and Technology. Patricia has been a member of the NAWCWD GPS/INS Branch since 2002 and has been involved with navigation error analysis, antenna measurement techniques, and GPS jamming efforts. Patricia is currently actively engaged in the system analysis of navigators for weapon system performance, along with the analysis of RF propagation over rough terrain conditions.

Matt Boggs received his BS in Electrical Engineering from New Mexico Institute of Mining and Technology. Matt has been a member of the NAWCWD GPS/INS Branch since 1989 and has been involved with design and implementation of missile hardware-in-the-loop simulation, navigation error analysis, antenna measurement techniques and GPS jamming efforts. Matt is currently working on low-cost instrumentation techniques for range applications.

Brent Larson received his BS in Electrical Engineering from Montana State University. While at NAWCWD China Lake, Brent has been involved in optics-based physics research, and weapon systems electromagnetic susceptibility and compliance testing. Brent has been actively engaged in the construction of embedded electronics and analysis of weapon system performance while with the NAWCWD GPS/INS Branch.

ABSTRACT

Many modern aircraft depend on the Global Positioning System (GPS) for navigation. This reliance on GPS navigation in conjunction with the addition of more GPS satellites in earth's orbit in the near future dictates that there be a means of simulating the effects of GPS performance during the takeoff and landing flight trajectories for commercial airliners to ensure the safety of the passengers. The GPS/INS Branch at the Naval Air Warfare Center Weapons Division in China Lake, California was given the task of determining a means of simulating the performance of GPS over the takeoff and approach trajectories of the commercial airlines at two airports across the world under actual GPS performance rather than specified performance. Data representative of aircraft approaches to London Heathrow airport are presented in this paper. This simulation was conducted by modeling GPS performance (i.e. CEP, DOPs, etc.) for representative civil aviation trajectories at the two airports using MATLAB. Performance was modeled via a Monte Carlo technique to minimize impacts of constellation geometries over time. This paper begins by discussing the issues that determined the need for this simulation. Following this discussion, the paper focuses on the assumptions needed to model the actual performance of the Global Positioning System in the simulation, the implementation of the simulation, and the results found during the simulation.

INTRODUCTION

The performance of GPS navigators for mid-course guidance under "real world" conditions is a growing concern. This concern is driven by the realization of the user community that the system level performance is consistently much better than the minimum performance levels that GPS is specified to yield.

The NAWCWD GPS/INS Branch was commissioned to perform an analysis of GPS receiver performance for an airborne platform using "real world" GPS performance values. The case of an airborne platform in a landing configuration was chosen as the principle case for investigation. This decision reflects the greater impact of a mid-course navigation system on an airborne platform's performance as seen in the landing case, rather than the take-off case.

BACKGROUND

The system level analysis performed as part of this study was conducted as part of an antenna effects study. The antenna effects study consisted of investigating the impact of an antenna with reduced field of view on the system-level performance of a GPS receiver system. This study was motivated by an interest in mitigating groundborne GPS interference sources for airborne platforms.

The primary flight regime investigated in this analysis was the case of an aircraft in the landing stage. This portion was deemed to be a more critical stage for aircraft than the takeoff portion, as the landing is heavily impacted by midcourse guidance.

This study utilizes a generalized civil aviation flight profile for a McDonnell-Douglas (Boeing) MD-11 air freight aircraft[1]. This flight profile provides a representative flight trajectory that incorporates the major degrees of freedom for a "generic" airliner, including representative degrees of aircraft pitch and roll maneuvers. The trajectories used by this study are not meant to be specific case studies.

ASSUMPTIONS

In order to perform this study, several assumptions were required to model the GPS performance.

The modeling required three antenna assumptions:

(1) The antenna boresight was normal to the airframe waterline.
(2) The antenna was located one-quarter the length of the aircraft from the nose of the aircraft.
(3) The half-cone angle used was 70 degrees.

To determine the GPS performance over different areas, two airport locations were chosen.

(1) Airport 1 (Los Angeles International Airport): 33° 56' 33" N, 118° 24' 29" W
Elevation: 126 feet
(2) Airport 2 (Heathrow International Airport): 51° 28' 37" N, 0° 27' 35" W
Elevation: 80 feet

The model was specified to use two different flight trajectories (take-off and landing) to analyze the GPS performance over the course of both flight trajectories. Figure 1 shows a plot of the aircraft's altitude over time for the landing.

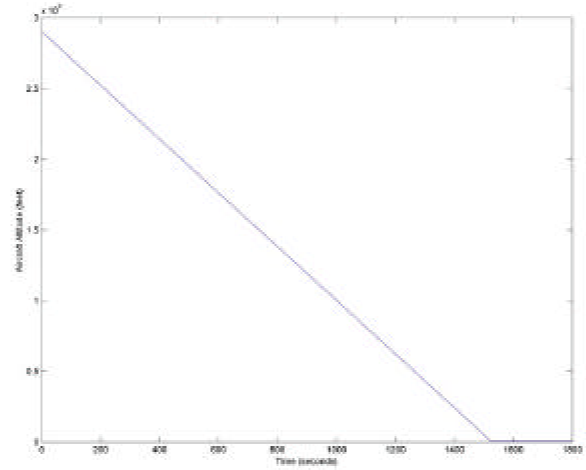

Figure 1. Aircraft Altitude vs. Time

The take-off and landing flight trajectories for commercial airliners were generated using the fundamental line formula ($y = mx + b$) to estimate the trajectories
where:

y = aircraft's altitude

m = slopes for the flight trajectories ((+) if take-off; (-) if landing)

x = time in seconds for a given altitude

b = airport's elevation (take-off) or cruise altitude (landing)

The assumptions made for the generation of the flight trajectory:

(1) Flight trajectory for take-off begins when aircraft wheel's leave the runway
(2) Flight trajectory for landing begins when aircraft begins descent.
(3) The simulation time starts at zero (0).
(4) The aircraft's cruising altitude is 29,000 feet.
(5) The total time for the flight profile is thirty (30) minutes (or 1800 seconds).

(6) The aircraft is flying from East to West for calculation simplification.
(7) The yaw is negligible over the course of the flight profile and therefore equal to the direction the aircraft is flying (270°).
(8) The aircraft performs a roll from 0° to +25° to 0° to -25° to 0° during the middle portion of the flight profile.
(9) The aircraft has a pitch of +6.5° during take-off trajectory and slowly decreases to +4.0° when approaching cruising altitude.
(10) The aircraft has a pitch of –4.5° during the landing trajectory and slowly increases to +1.5° when approaching ground level.
(11) The aircraft has a constant (+)17 feet/second rate of climb (slope) during the take-off trajectory.
(12) The aircraft has a constant (-)19 feet/second rate of descent (slope) during the landing trajectory.
(13) The horizontal speed of the aircraft varies depending on the aircraft's altitude.
(14) Ground elevation to 10,000 feet: 250 knots (approximately 422 feet/second).
(15) 10,000 to 29,000 feet: 0.8 mach (approximately 880 feet/second)
    a. Gradual acceleration from 250 knots to 0.8 mach over a 60 second time interval after 10,000 feet during take-off trajectory.
    b. Gradual deceleration from 0.8 mach over a 60 second time interval around 10,000 feet during landing trajectory.
(16) A GPS antenna is mounted to the top of the aircraft. It is masked by the fuselage with an elevation angle of 0° and by the vertical tail with an elevation angle of 30° for an azimuth range of 170° to 190° relative to the nose of the aircraft.
(17) A 5° mask of the Earth is used to determine LOS for the satellites.

The model used the GPS almanac for Week 1150 for GPS satellite health information.

The analysis was iterated in a Monte Carlo approach over 100 runs during a six (6) month period (1 January 2003 – 1 July 2003).

The model used a GPS user range error (URE) total value of 6.3 meters. This value was found on the Intec Americas website:

http://www.intecamericas.com/techbulletinGPSselecavail.htm

Intec America determined that with the elimination of selective availability (SA), the raw positional accuracy will be 15 - 20 meters, and many users will achieve even better results. In one of their tests with a dual-frequency receiver, SA caused 95% of the points to fall with in a radius of 45.0 meters; without SA, 95% of the points fall within a radius of 6.3 meters.

IMPLEMENTATION

The following section discusses the code implementation used in this simulation in order to analyze the GPS performance given a specific trajectory, time period, half-cone angle, and airport location.

FLIGHT TRAJECTORIES

The first phase in the implementation of the analysis is to generate the take-off and landing trajectories. This is done using the fundamental line equation ($y = mx + b$). The slopes (or rates) will remain constant over the course of the flight trajectories. The take-off flight trajectory's rate of climb is +17 feet/second. The landing flight trajectory's rate of descent is –19 feet/second.

The y-intercepts for the take-off trajectories are the elevations at each of the airports (see Table 1).

Airport	Elevation (feet)
Los Angeles International Airport	126
Heathrow International Airport	80

Table 1: Takeoff Trajectory Y-Intercepts

The y-intercept for all the landing trajectories is the cruising altitude of 29,000 feet.

The aircraft's altitude (y) over the course of the simulation can be calculated using the rate of climb/descent (m), the simulation time specified for the flight trajectory (x), and y-intercepts (b). The formula used to determine the aircraft's altitude during the take-off trajectory can be seen in Equation (1). The formula used to determine the aircraft's altitude during the landing trajectory can be seen in Equation (2).

$$\text{take off altitude} = \text{rate of climb} * \text{time} + \text{airport elevation} \quad \textbf{(1)}$$

$$\text{landing altitude} = \text{rate of descent} * \text{time} + \text{cruising altitude} \quad \textbf{(2)}$$

Aircraft Position

The next phase in the implementation of the analysis is to determine the aircraft's position. The aircraft's position consists of its six degrees of freedom (6 DOFs). The 6 DOFs are roll, pitch, yaw, latitude, longitude, and altitude which was calculated in the previous phase.

The yaw is negligible over the course of the flight profile, it is set to 270 since the aircraft is flying in an east to west direction in order to simplify calculations for this study.

The roll is generated by inserting a S-curve type maneuver in the middle of the flight profile. The aircraft slowly increases its roll from level (0°) to +25° and then slowly levels again to 0°. It then slowly decreases from level (0°) to -25° and then slowly levels to 0° again. The roll is incremented/decremented by 1°/second for this maneuver.

The pitch during the take-off profile is generated by slowly incrementing by an increment of 0.5°/second the pitch from level at 0° to 6.5° at the beginning of the flight profile. The pitch is then decreased by an increment of 0.5°/second until the pitch is 4.0° while approaching the cruising altitude of 29,000 feet.

The pitch during the landing profile is generated by decreasing the pitch from 4.0° to –4.5° by an increment of 0.5°/second at the beginning of the flight profile. The pitch is then increased by an increment of 0.5°/second until the pitch is 1.5° while approaching the airport's elevation.

The latitude stays constant at the airport's coordinate value since the aircraft is only flying east to west.

The longitude, during the take-off flight profile, is generated by calculating the horizontal distance the aircraft has traveled from the airport using the distance formula (shown in Equation 3and 4) and subtracting this distance from the airport's longitude (shown in Equation 5). The rate that is used in this equation varies depending on the aircraft's altitude. If the aircraft is between ground level and 10,000 feet, the aircraft's horizontal speed is 250 knots (approximately 422 feet/second). If the aircraft is above 10,000 feet, the aircraft's horizontal speed is 0.8 mach (approximately 880 feet/second).

*distance = rate * time* **(3)**

*horizontal distance = speed of aircraft * time* **(4)**

longitude position = airport longitude – horizontal distance **(5)**

The longitude, during the landing flight profile, is generated by calculating the horizontal distance the aircraft needs to travel to the airport using the distance formula (shown in Equation 3 and 4) and adding this distance to the airport's longitude (shown in Equation 6). The rate that is used in this equation varies depending on the aircraft's altitude. If the aircraft is between ground level and 10,000 feet, the aircraft's horizontal speed is 250 knots (approximately 422 feet/second). If the aircraft is above 10,000 feet, the aircraft's horizontal speed is 0.8 mach (approximately 880 feet/second).

longitude position = airport longitude + horizontal distance **(6)**

GPS CALCULATIONS

The next phase in the implementation of this analysis is the GPS calculations. The GPS features that are calculated during this phase are line-of-sight (LOS) using Earth and body masking, the numbers of satellites tracked over the course of the simulation, dilution of precisions (DOPs), fifty and ninety percent (50% and 90%) circular error probable (CEP), vertical error, and total position error. These calculations are done using the functions in Constell's Constellation Toolbox software for Matlab.

CODE FLOW CHART

The program for the simulation can be broken down into the the flow chart which is shown in Figure 2.

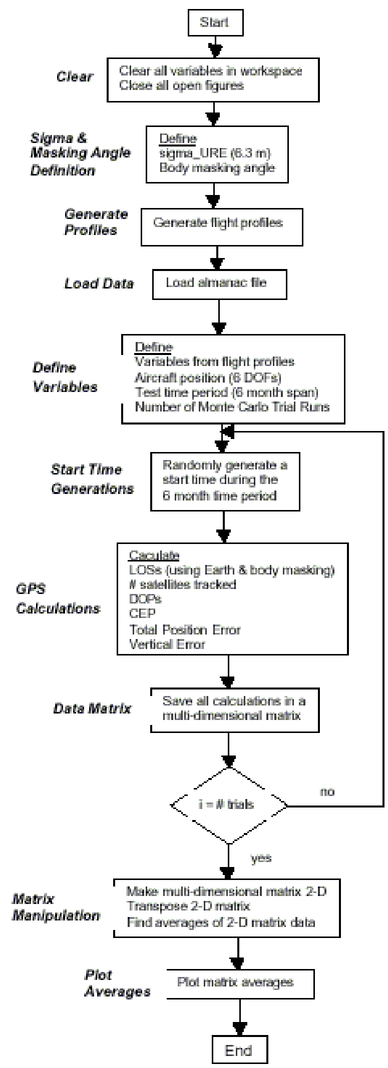

Fig. 2. Code Flow Chart

RESULTS

The results for the London Heathrow International Airport during the landing profile show that the average number of satellites visible does very depending on the positioning of the aircraft during the flight trajectory (i.e., pitch, roll, altitude, etc.). This is illustrated below in Figure 3.

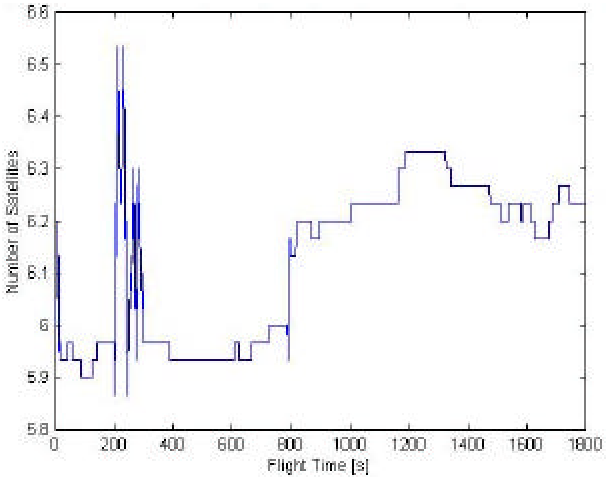

Fig. 3. Average Number of Satellites vs. Flight Time: London Heathrow

The average CEP for London Heathrow International Airport does not seem to be affected by the change in pitch. However, it does change significantly during the aircraft's change in position due to the roll. This is illustrated below in Figure 4.

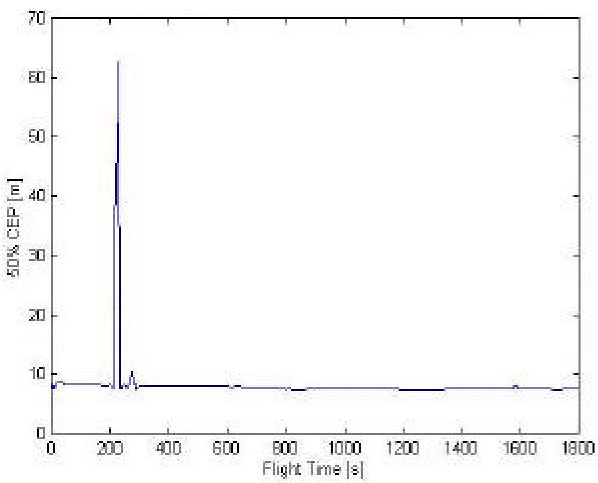

Fig. 4. Average CEP vs. Flight Time: London Heathrow

The average vertical error seen at London Heathrow International Airport is affected by both the aircraft's change in pitch and roll. This is seen in Figure 5.

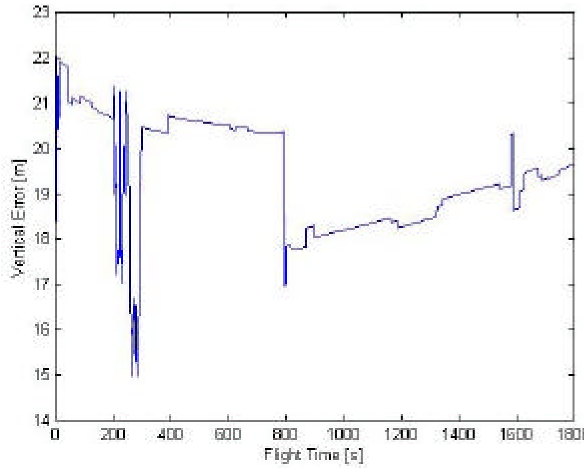

Fig. 5. Average Vertical Error vs. Flight Time: London Heathrow

The average total position error seen at London Heathrow International Airport is strongly influenced by the average vertical error and therefore is also affected by both the aircraft's change in pitch and roll. This is illustrated below in Figure 6.

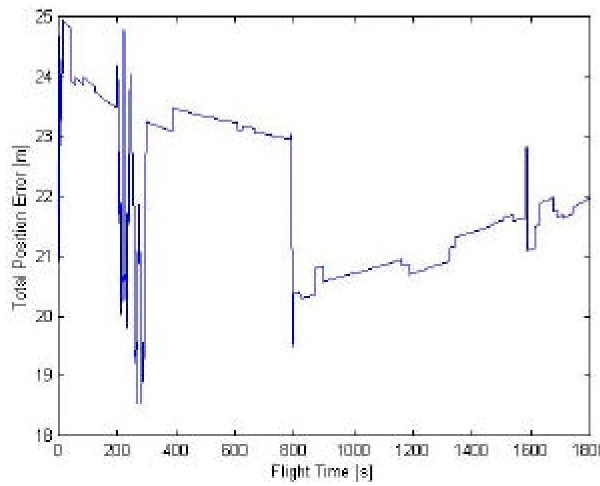

Fig. 6. Average Vertical Error vs. Flight Time: London Heathrow

CONCLUSIONS

This study was performed using actual constellation performance. The results that were shown are consistant with empirical test data that has been collected during tests performed at the NAWCWD China Lake test ranges. These results also show better positional performance than when modeled with the ICD-200 “spec” constellation performance.

The positioning performance with the reduced antenna field of view is still very viable for civil aviation GPS performance. This indicates that groundplane nulling antennas do not greatly degrade the GPS performance during our flight trajectories.

This modeling effort is still on-going and evolving. This model is still being evaluated and the results are currently being studied for further validation for future use.

ACKNOWLEDGEMENTS

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[1] Albert Heidinger, personal communications, May 2003.