

Design of Global Positioning System Receivers for Integrated Inertial Navigation Systems *

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Abstract

There is much interest in integrated navigation using the Global Positioning System and Inertial Measurement Units (accelerometers and gyroscopes). The results reported in this paper quantify integrated navigation performance as a function of GPS receiver design parameters. The specific application considered is missile navigation.

I. Introduction

Most IMUs have relatively good short term accuracy – that is, they have very little high frequency error. On the other hand, GPS has relatively good long term accuracy – that is, it has very little low frequency error. This combination makes Kalman filter-based integrated GPS/IMU navigation a natural application of GPS, giving a user the best of both worlds [3, 5].

Navigation performance can be quantified by Position and Velocity Spherical Error Probable (PSEP and VSEP). SEP is defined as the 50th percentile probability radius of the navigation solution. That is, there is a 50% probability that the vehicle position (velocity) is within PSEP (VSEP) of the navigation solution.

Integrated GPS/IMU navigation systems tend to use GPS receivers which are either underdesigned or overdesigned. That is, the receivers provide either much better or much worse performance than required. This paper presents results showing the effect of various GPS user segment parameters on integrated navigation performance. The results in this paper can be used to determine which receiver design is well-suited to a user's particular needs. A more complete treatment of this topic can be found in [7].

GPS Errors

A GPS receiver measures position by tracking a pseudo-random (PR) binary code transmitted by the GPS satellites. This is typically done with a 50 Hz delay lock loop (DLL) [8]. A GPS receiver measures velocity by tracking the carrier which is modulated by the PR code. This is done with a phase-locked loop (PLL) [6]. The phase measurements are called doppler ranges, and the difference between two successive doppler ranges is called a delta range. The PLL is rate-aided by the IMU so that phase lock is maintained during high vehicle dynamics.

*This work was supported by Independent Research and Development Project 93288305, sponsored by the Guidance, Systems and Controls Department of the TRW Systems Integration Group in San Bernardino, CA.

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Error	Standard Deviation
Satellite Position	13 feet
Satellite Velocity	0.005 feet/sec
Clock Phase	10 nsec
Clock Frequency	10^{-6} ppm
DLL Tracking	2 - 10 feet
PLL Tracking	.005 - .02 feet
Ionospheric Range	8 - 25 feet
Ionospheric Doppler Range	0.02 - 1.6 feet
Tropospheric Correction Scale Factor	0.3
Antenna Phase Center	0.1 feet
Antenna Phase Response	20 - 80°
GPS/IMU clock offset	1 msec

Table I: GPS Errors

A fairly complete list of GPS errors is given in Table I. The satellite position and velocity and the antenna phase center errors have three components each. The DLL and PLL tracking errors vary depending on such things as antenna design, vehicle dynamics, and atmospheric noise. The ionospheric errors vary depending on whether the GPS receiver tracks one or two frequencies. The antenna phase response error depends on the fidelity of the characterization of the antenna phase response. See [7] for a more detailed discussion of the GPS errors. The variances of the GPS errors were derived from the literature [4] and flight test experience [1].

II. Simulation Study

The simulation study is based on a representative missile test trajectory. The missile's strapdown IMU consists of three accelerometers and three gyros, and contains 76 error terms – 10 initial condition errors, 33 accelerometer errors, and 33 gyro errors [2]. The missile's GPS receiver tracks six satellites and the flight computer derives an integrated GPS/IMU navigation solution once per second.

A full order Kalman filter contains 164 states – 76 IMU error states, 4 global GPS errors (GPS/IMU clock offset and three components of antenna phase center error), and 6×14 satellite-specific errors. It may not be feasible to run such a large filter in real time, so two reduced order filters were designed. The medium order filter contained 31 IMU error states and 22 GPS error states, and the lowest order filter contained 16 IMU error states and 19 GPS error

states. The unmodelled errors were compensated for by increasing the *a priori* variance of the modelled errors, and adding additional delta range measurement noise to the filter.

Each SEP data point in this study was determined by conducting a Monte Carlo analysis of 100 samples. Since SEP at payload deployment determines weapon delivery accuracy, SEP at 184 seconds following launch (Stage 3 burnout) was used as a scalar measure of integrated navigation performance.

Figure 1 shows the GPS-only VSEP. It is seen that for a single frequency receiver, a four-fold improvement in the antenna phase response results in only a marginal improvement of VSEP. This is because the antenna error is dominated by the ionospheric error. It is also seen that the use of a dual frequency receiver buys only a small advantage over a single frequency receiver at low altitudes, but it buys a large advantage at high altitudes (later in the flight). This is because of the dominance of tropospheric errors at low altitudes. For a dual frequency receiver at high altitudes, an improvement in the antenna can make a major improvement in GPS velocity performance.

Table II shows the integrated GPS/IMU SEP. We see that filter order has a large influence on VSEP. Figure 2 shows integrated GPS/IMU VSEP at payload deployment as a function of antenna phase error for a dual frequency receiver. Comparing Table II with Figure 2, we see that single frequency performance is much worse than dual frequency performance. But also note that a single frequency receiver with a full order filter can provide a better VSEP than a dual frequency receiver with a low order filter.

	Filter Order	Single Freq.	Dual Freq.
PSEP	Lowest	26.9 feet	22.7 feet
	Medium	26.4	20.1
	Full	26.3	19.6
VSEP	Lowest	0.1323 feet/sec	Figure 2
	Medium	0.0818	
	Full	0.0751	

Table II: Integrated GPS/IMU Spherical Error Probable at Payload Deployment

III. Conclusion

Integrated GPS/IMU navigation performance has been presented as a function of antenna phase error, single/dual frequency, and filter order. The results presented indicate that the most important decision to be made about a GPS receiver is whether to use a single or a dual frequency receiver. Filter order is also seen to be a critical parameter. If a dual frequency receiver is used, the quality of the antenna becomes important. The approach taken in this paper allows the user to specify a GPS receiver design

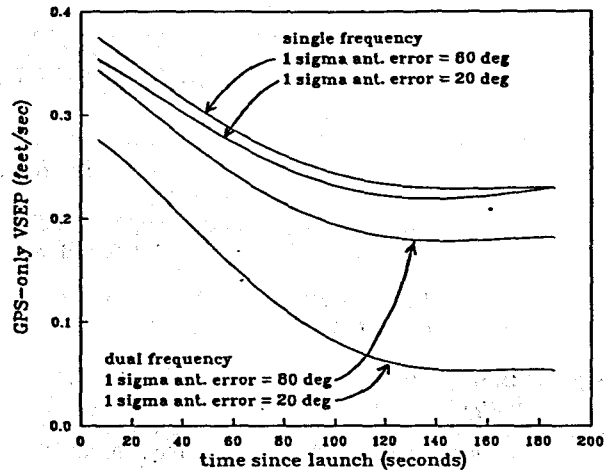


Figure 1: GPS-only Velocity Spherical Error Probable

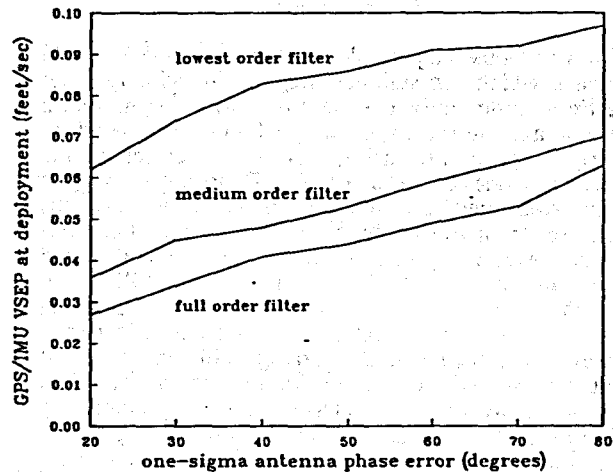


Figure 2: Integrated GPS/IMU Velocity Spherical Error Probable (Dual Frequency)

which provides enough accuracy, but which is not overly accurate and expensive. Full details can be found in [7].

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